Climate, Chemistry, Technology, and Society: a University Responsibility

Benton Lecture
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Harvard University

Climate, Chemistry, Technology, and Society: a University Responsibility

Backdrop: Consider the Scope, Scale and Rate of Change Taking Place, Driven By

- **Ideas Propelling Profound Shifts in Economic Structures and the Way the Emerging Generation Views Opportunity**
- **Globalization of Economic Competition That Accentuates the Difference Between Winners and Losers**
- **Major Developments in the Physical Sciences, Life Sciences, and the Revolution in Engineering Design**
- **Changes to the Physical, Chemical and Biological Structure of the Planet**
- **What This Implies for Changes in University Strategy**

Climate, Chemistry, Technology, and Society: a University Responsibility

Consider the United States in This Context

- Notable aspects within the US associated with these rapid changes are encouraging …….
- But many aspects are cause for major concern …..
- Given that science, technology, engineering design, etc. are now intimately interwoven with economics, law, public policy, and opportunities for young people,
- What does this imply for changes in university course structures?

Key Starting Point: **All university graduates today, independent of chosen concentration, face coming to terms with a number of critical questions:**

1.
What technical forces are shaping the modern world?

2.
Where are the frontiers of innovation and what implications do those advances hold for professional endeavors ...

3.
not just in technology, but also in international economics, government, ethics, journalism, public health, law and education.

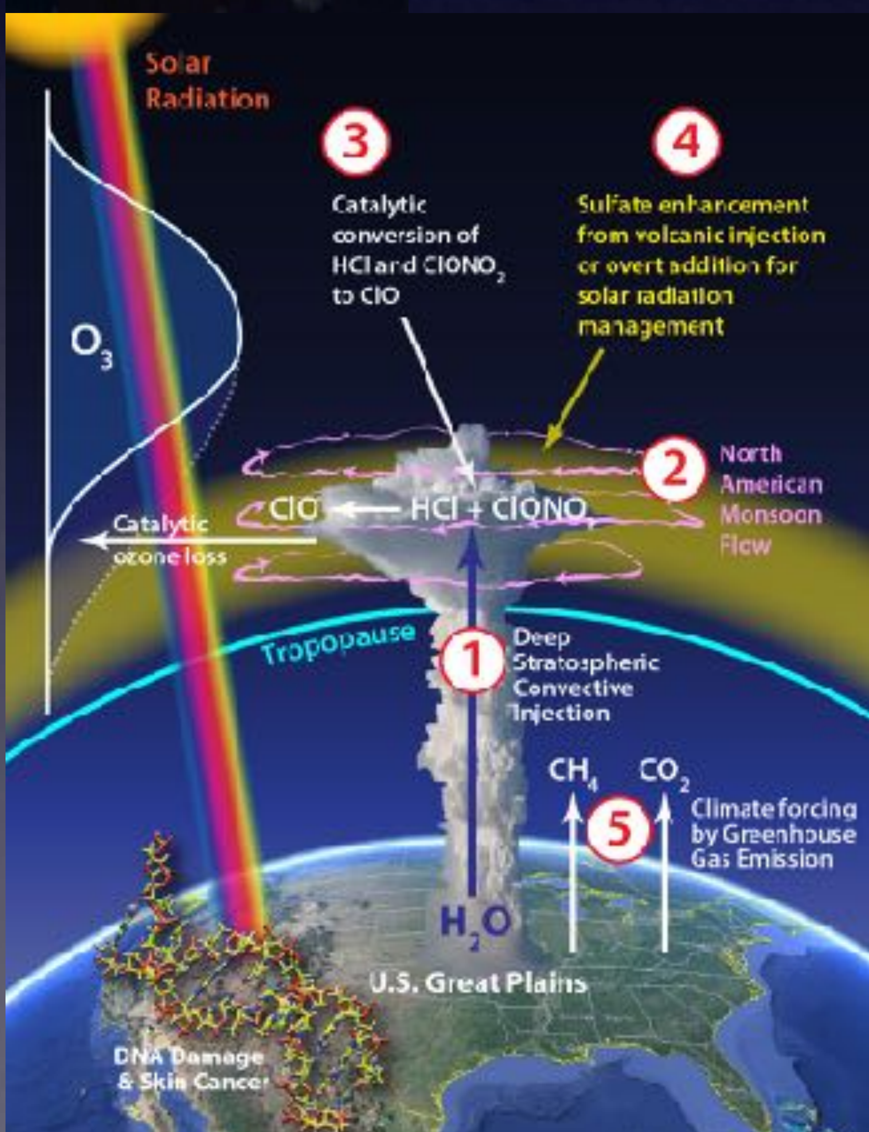
4.
Which public policy strategies are founded on sound scientific and technological understanding and which are not?

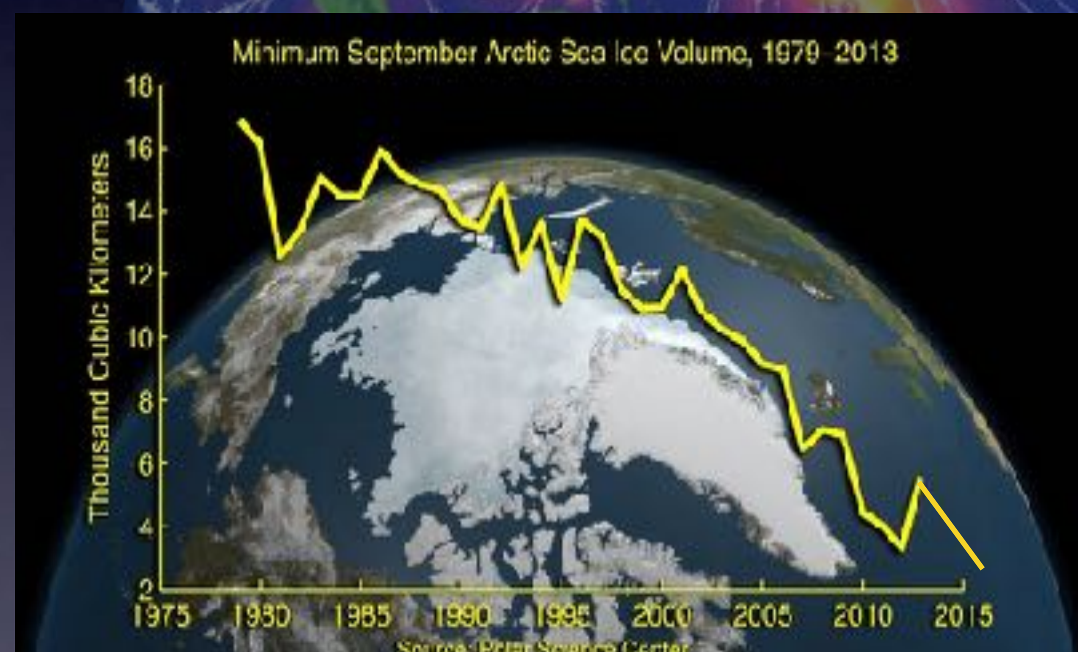
University responsibilities?

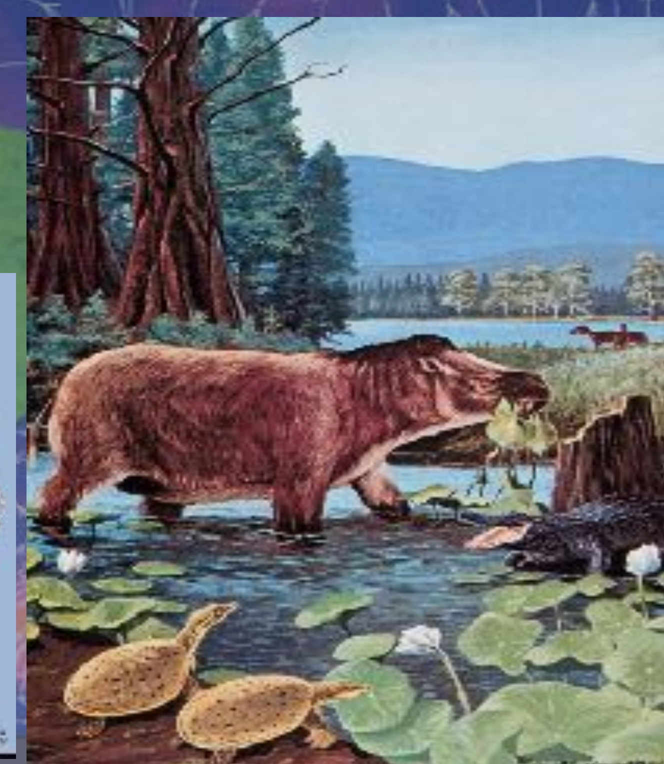
- to establish a state-of-the-art science/ technology curriculum to proactively and broadly addresses those emerging challenges; and
- but far more than that, to link those developments into the structure and function of the global enterprise in state and national governance, economics, law, international perspective, and moral leadership.
- Rather than discuss generalities …….

Explicit Example of the Scope, Scale and Rate of Change Taking Place:

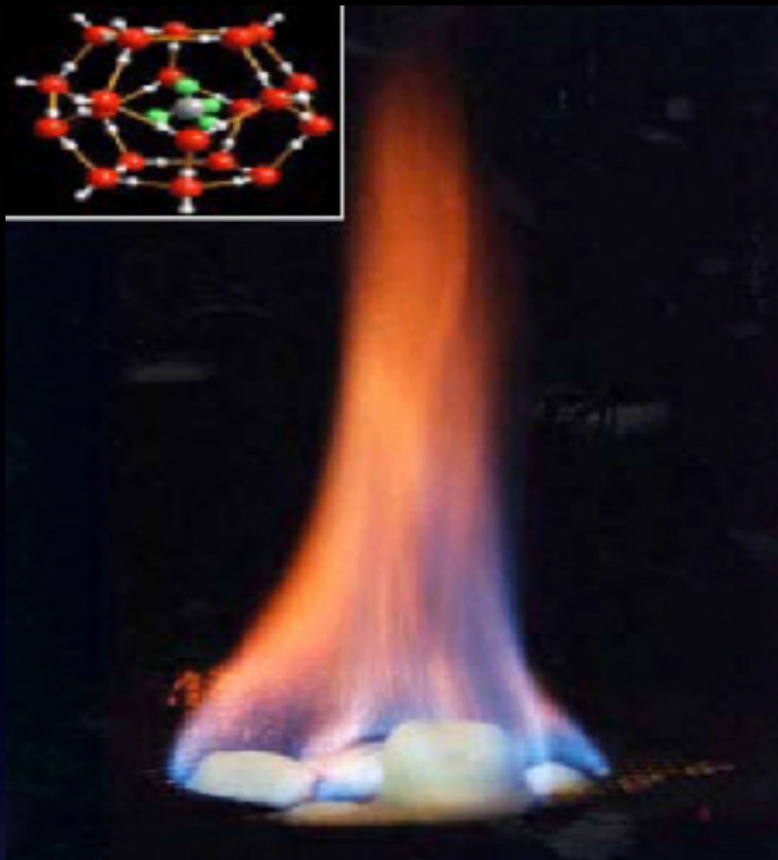
Changes to the Physical, Chemical and Biological Structure of the Planet to Investigate the Interlacing of Science, Technology, and Engineering with Education, Public Policy and Proactive Engagement With Unfolding Events.

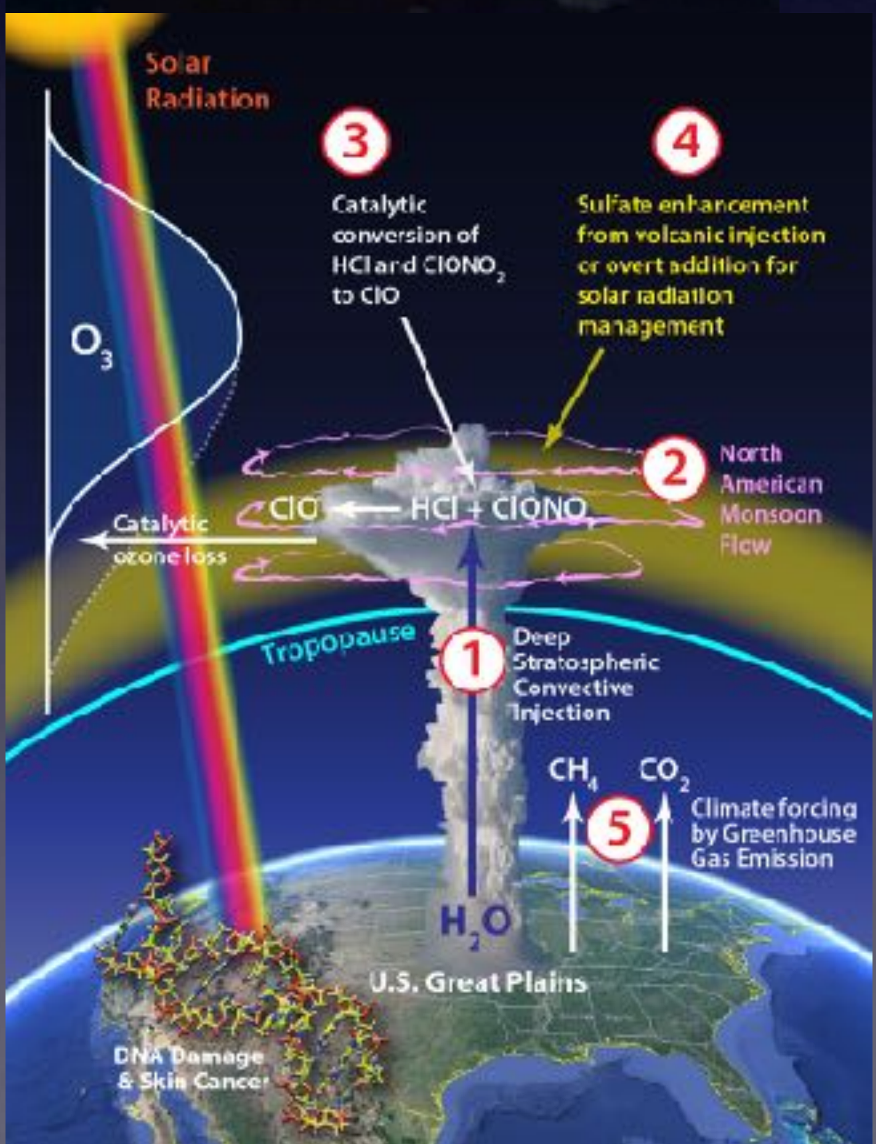


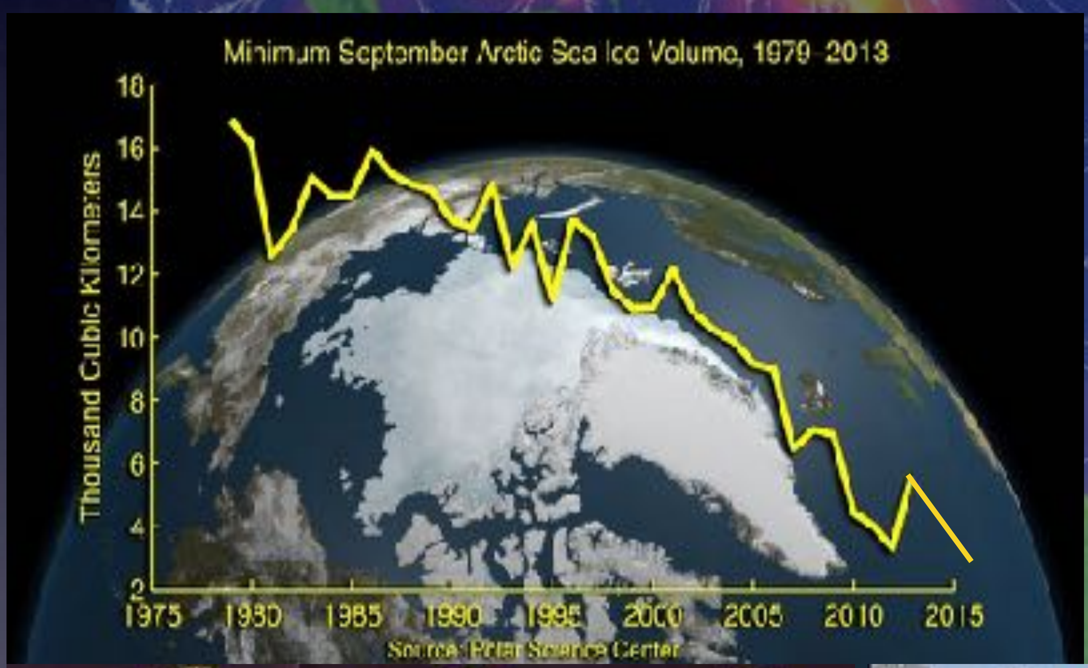


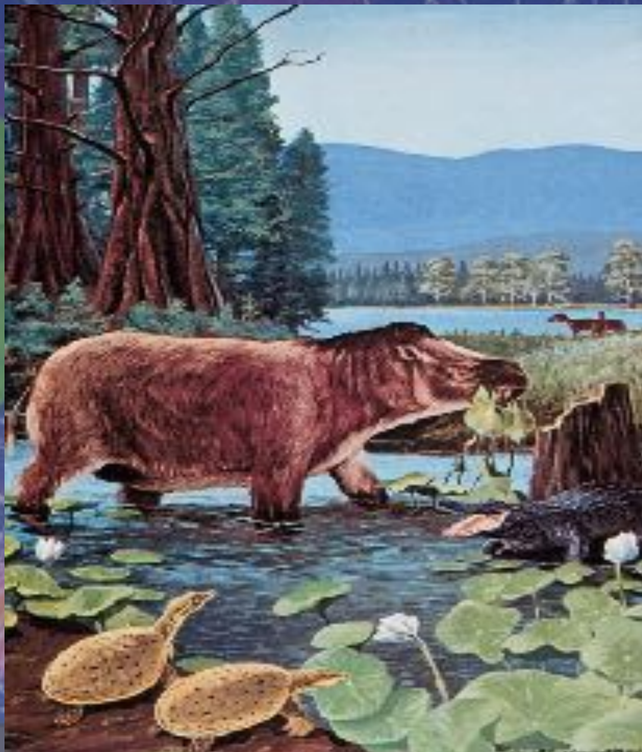


Recast the Perspective Regarding Climate Change: Turn From "Global Warming" to Feedbacks, Instability and the Time Scale for Irreversibility





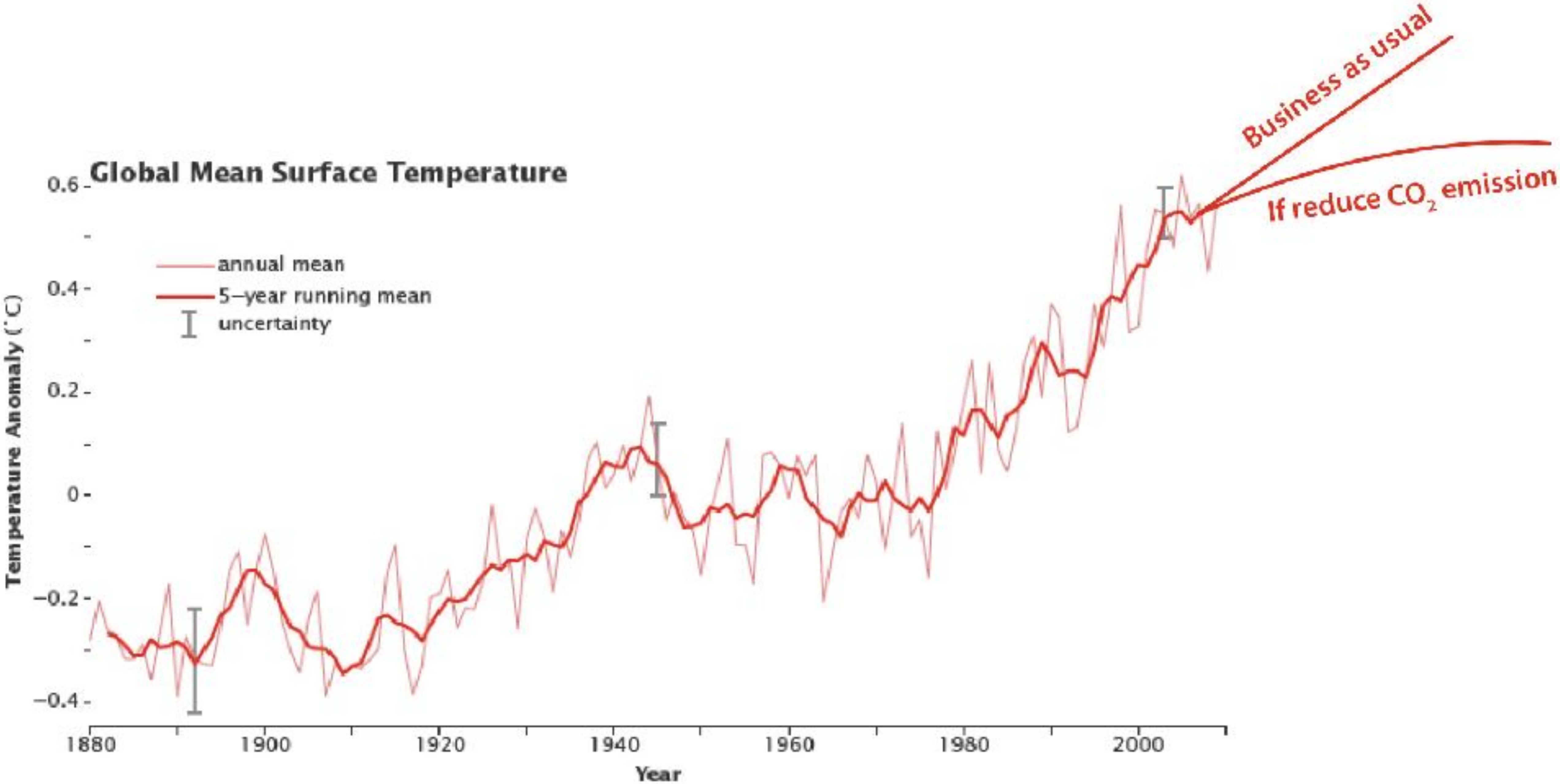




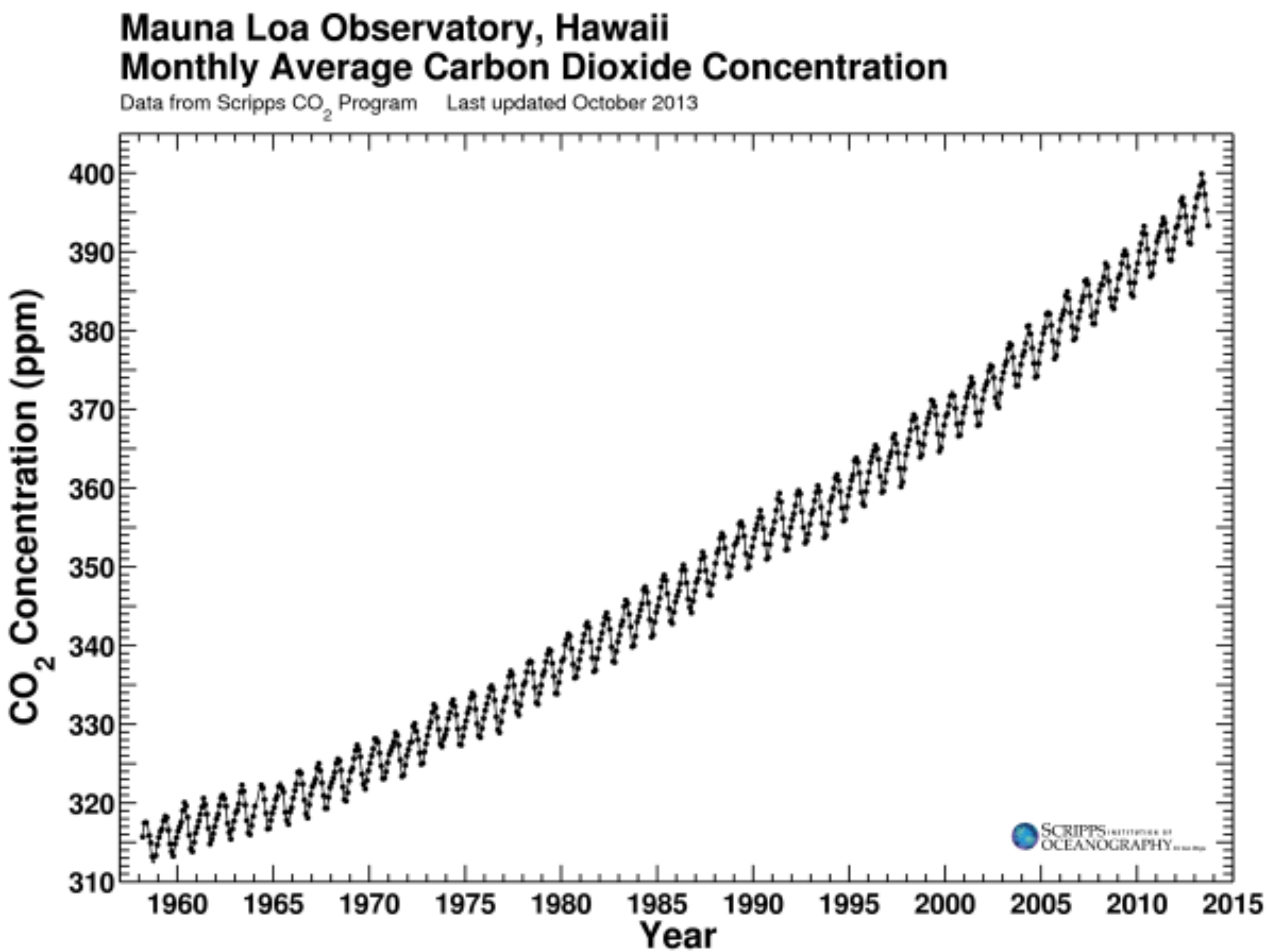
The Problem With the Term “Global Warming”:

It represents the average temperature increase over the entire globe, 70% of which is covered by ocean with an average depth of 3500meters

“Global Warming” Carries the Connotation of Small Changes in Temperature That are Reversible

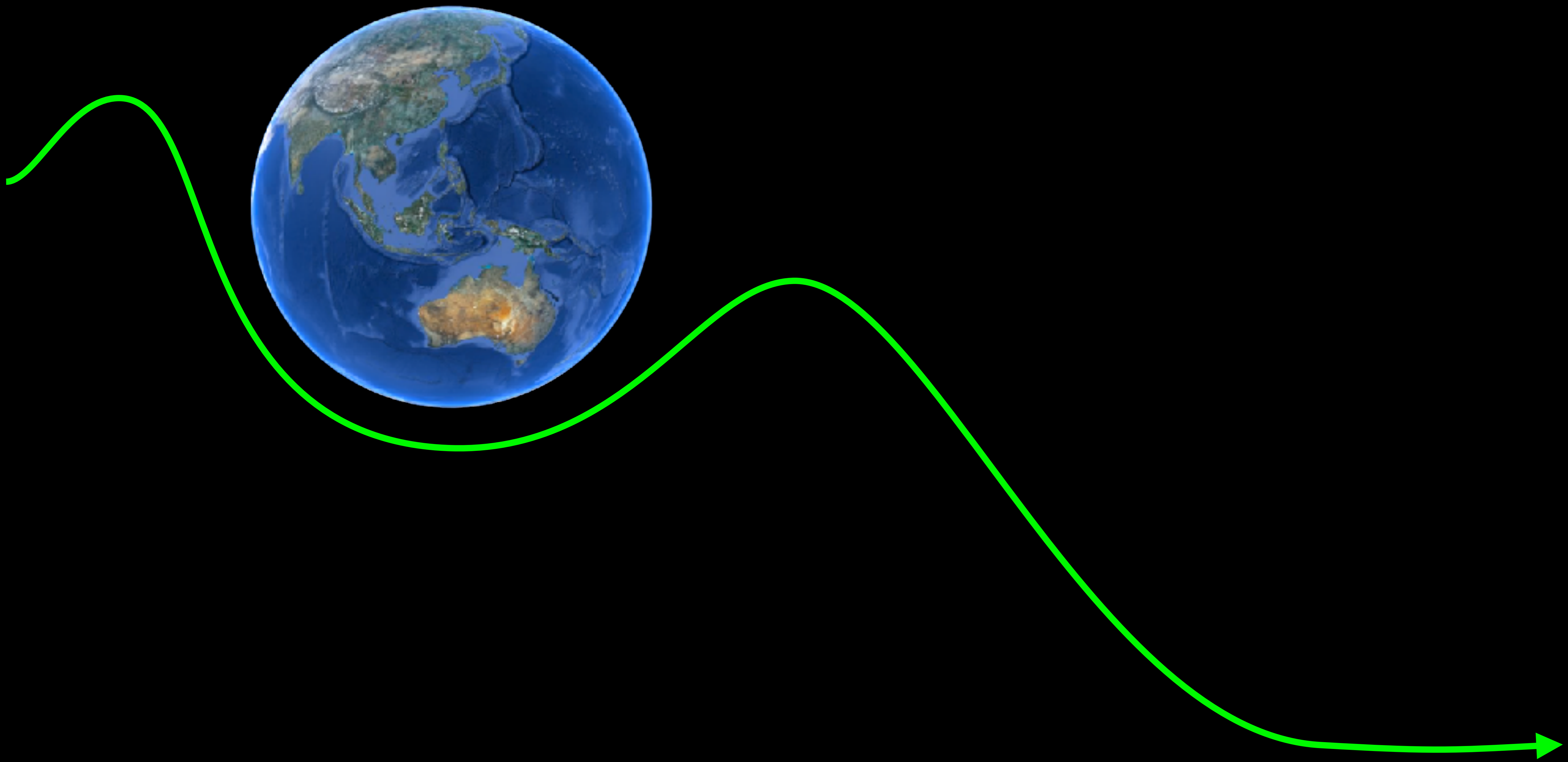


Keeling Curve for CO_2

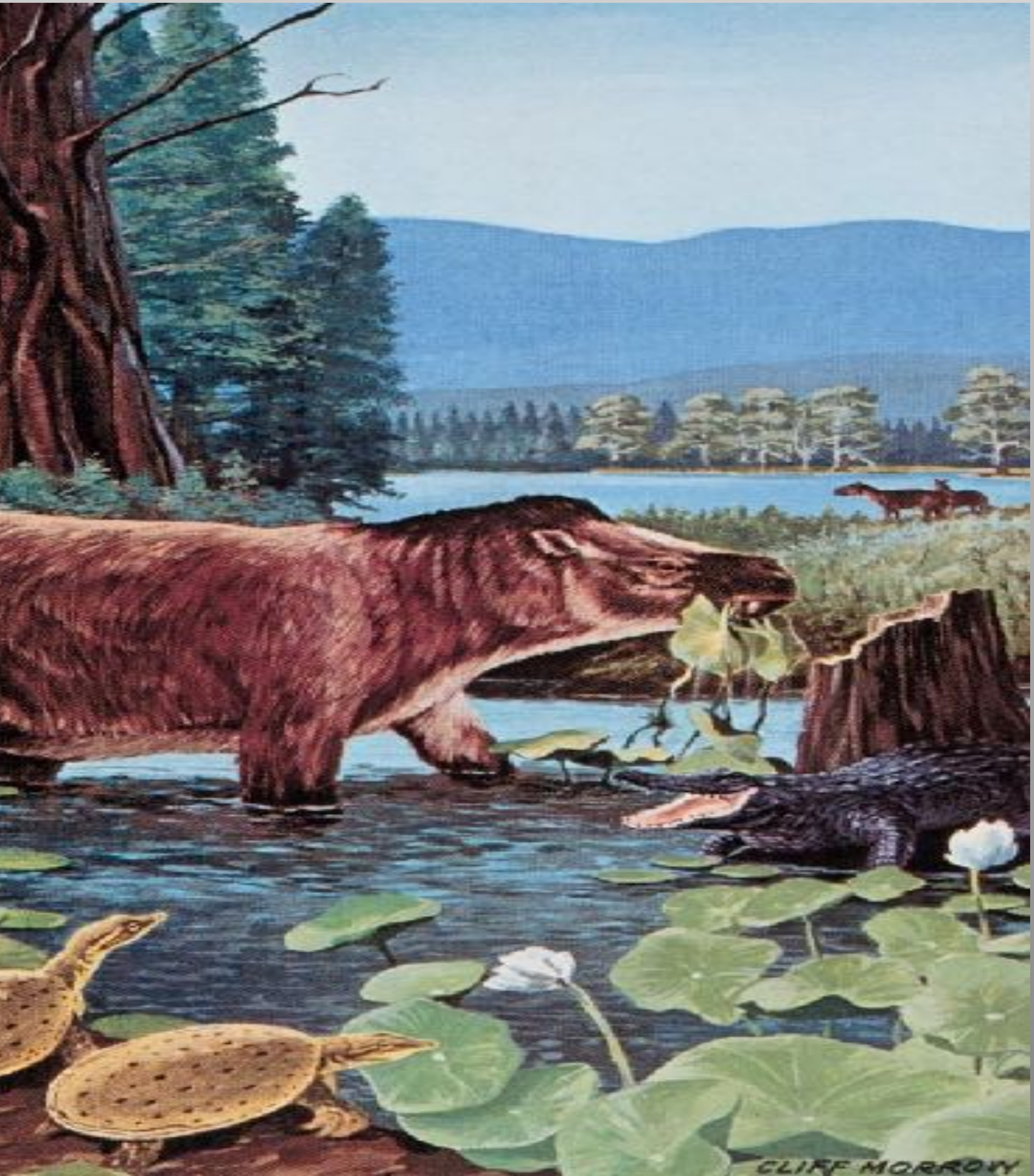


Irreversible Changes to the Climate Structure

Instability ⟷ **Irreversibility**



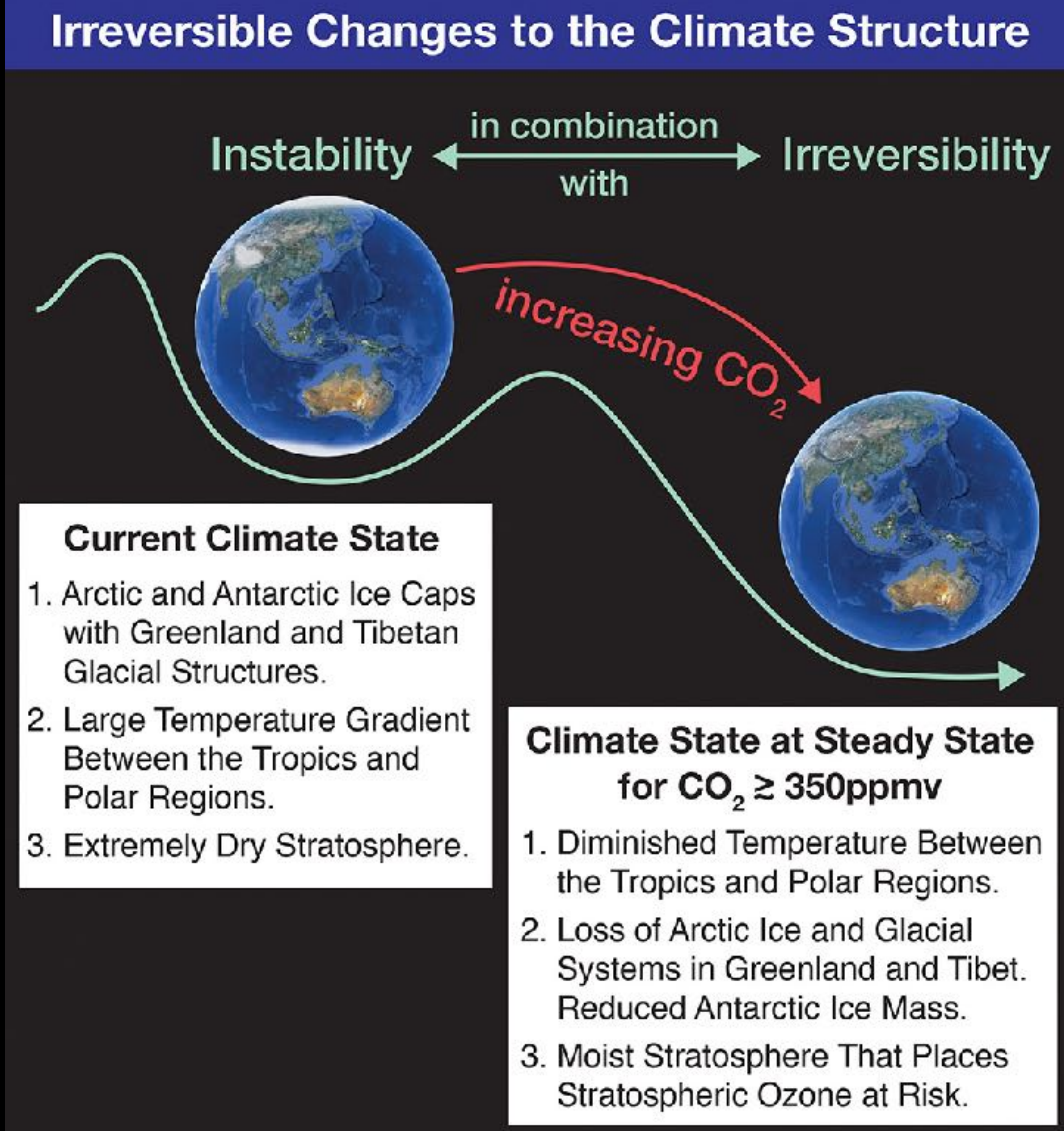
- The Paleo-Record Contains Key Information Concerning the Earth's Climate Structure at Elevated CO_2 Levels



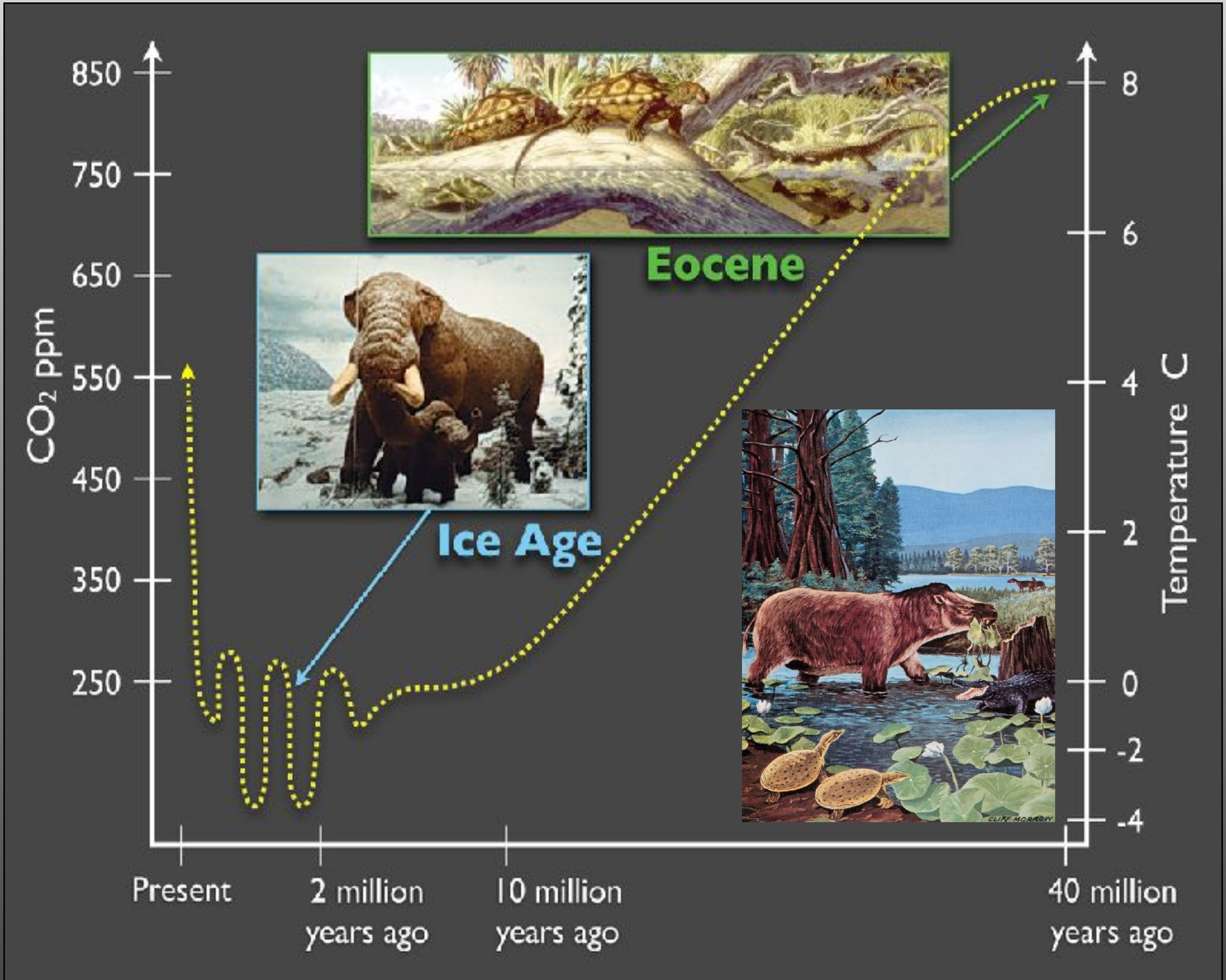
We know This From Studies of the Climate at ***Elevated Concentrations of Carbon Dioxide*** - The Eocene.

An artist's picture of the ***Arctic Ocean*** coast during the Eocene epoch, about 40 million years ago.

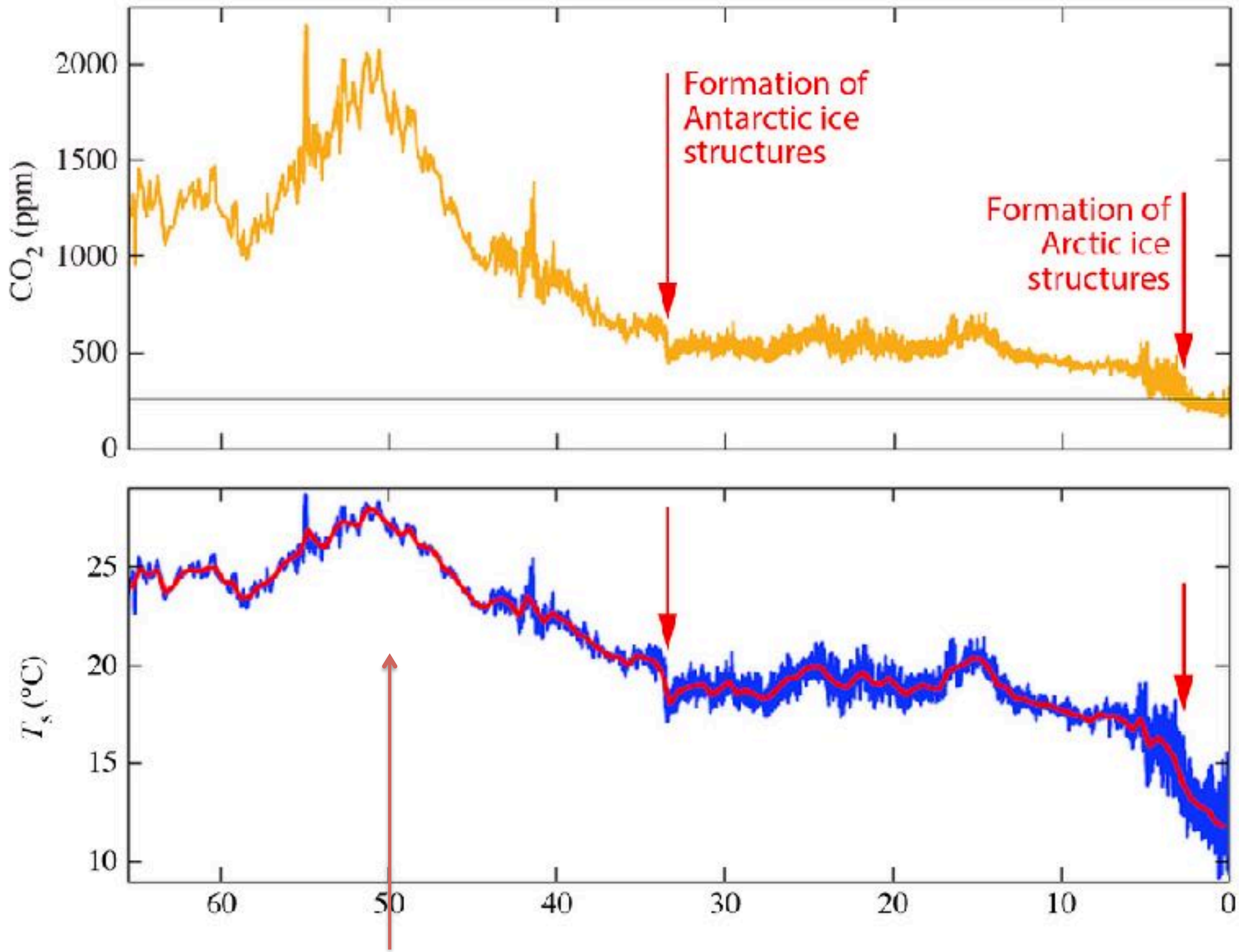
There was ***very little difference in temperature*** between the tropics and the polar regions.


Irreversible Changes to the Climate Structure
Instability
in combination
with
Irreversibility
increasing CO_2
Current Climate State
1. Arctic and Antarctic Ice Caps with Greenland and Tibetan Glacial Structures.
2. Large Temperature Gradient Between the Tropics and Polar Regions.
3. Extremely Dry Stratosphere.
Climate State at Steady State for $CO_2 \geq 350$ppmv
1. Diminished Temperature Between the Tropics and Polar Regions.
2. Loss of Arctic Ice and Glacial Systems in Greenland and Tibet. Reduced Antarctic Ice Mass.
3. Moist Stratosphere That Places Stratospheric Ozone at Risk.

What do we know from past climate stages?



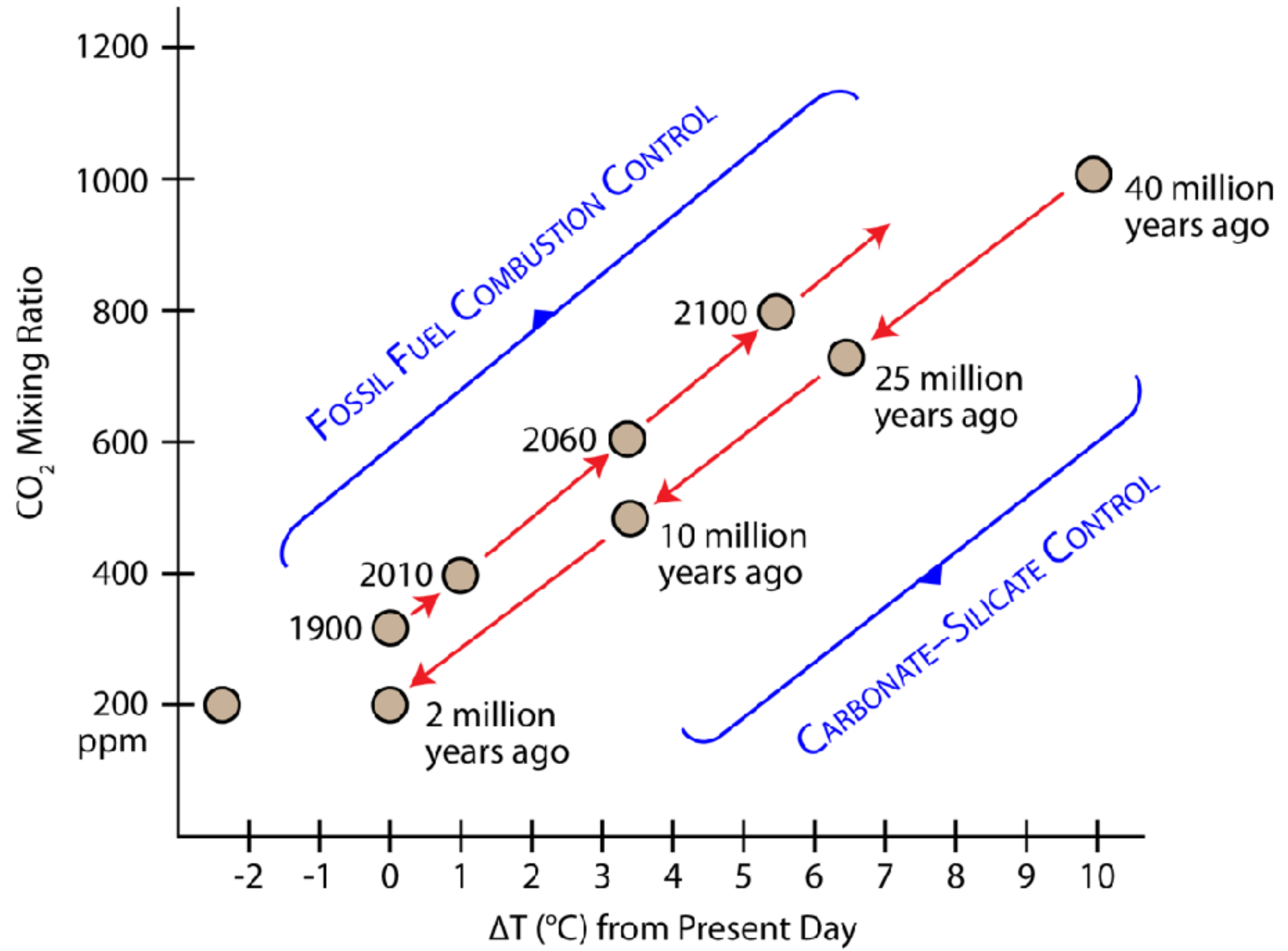
Stability of the climate state



Paleocene-Eocene Thermal Maximum

Hansen (2013)

Measured in CO_2 Years



“Global Warming” Carries the Connotation of Small Changes in Temperature That are Reversible

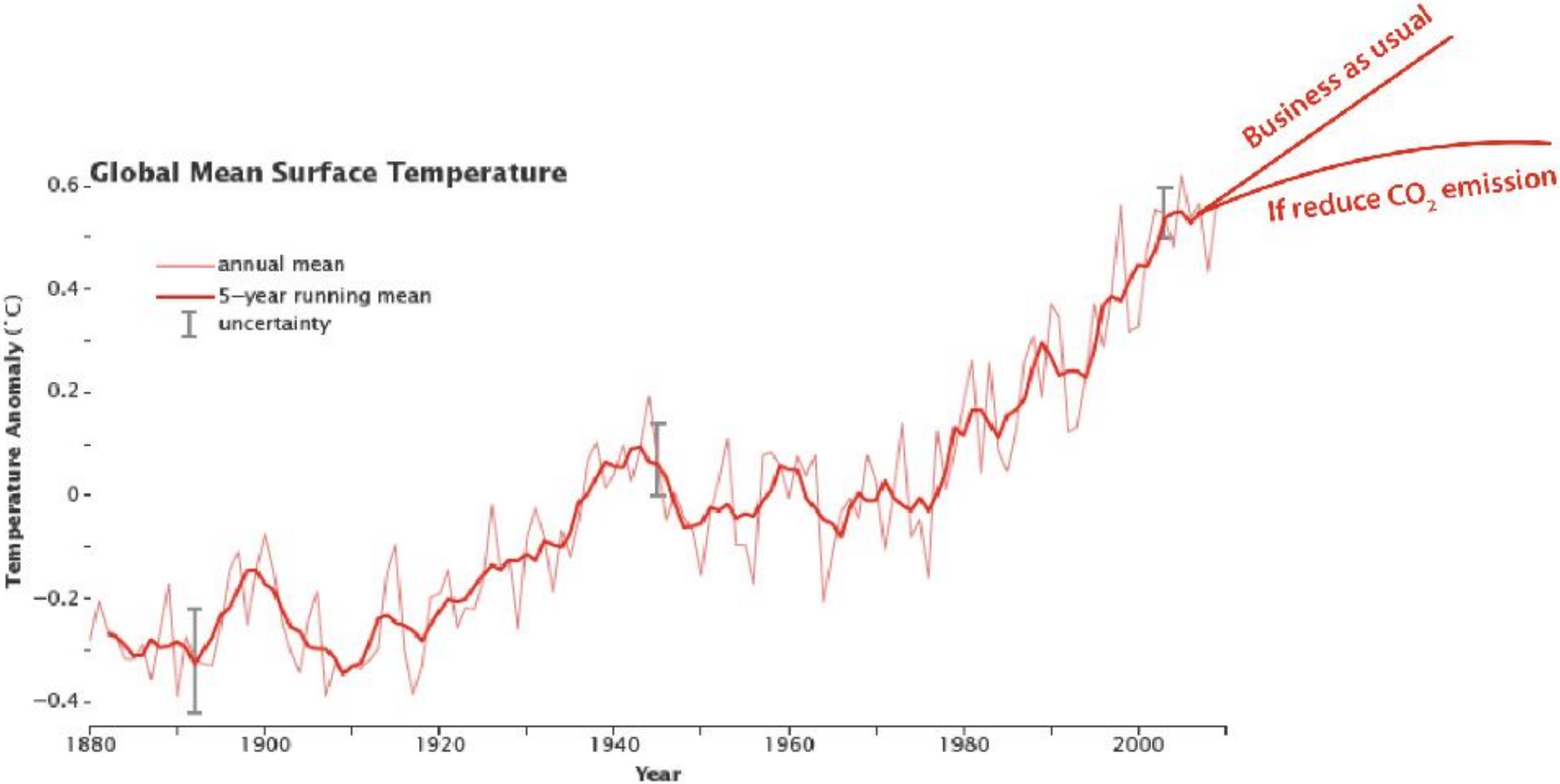
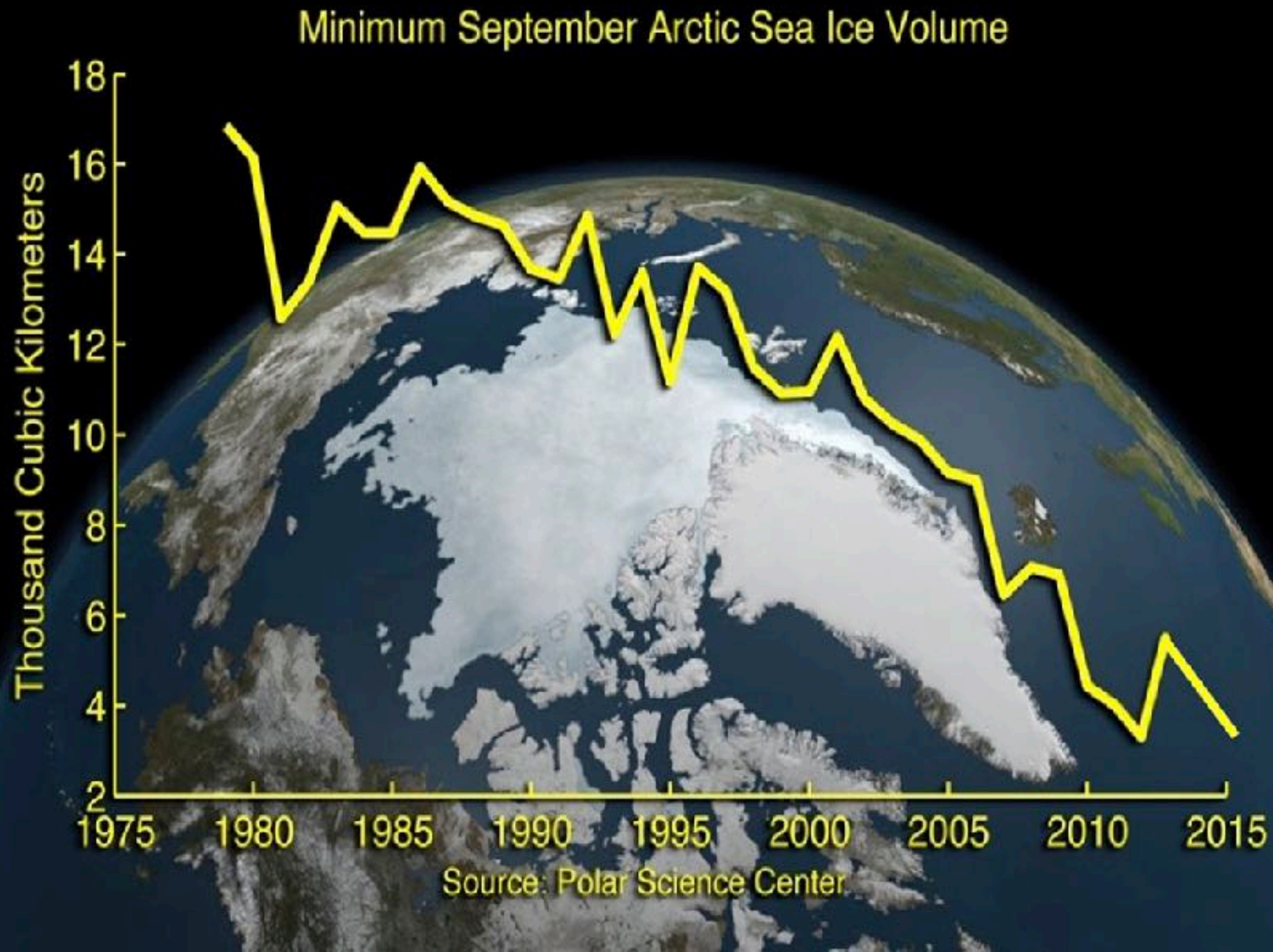
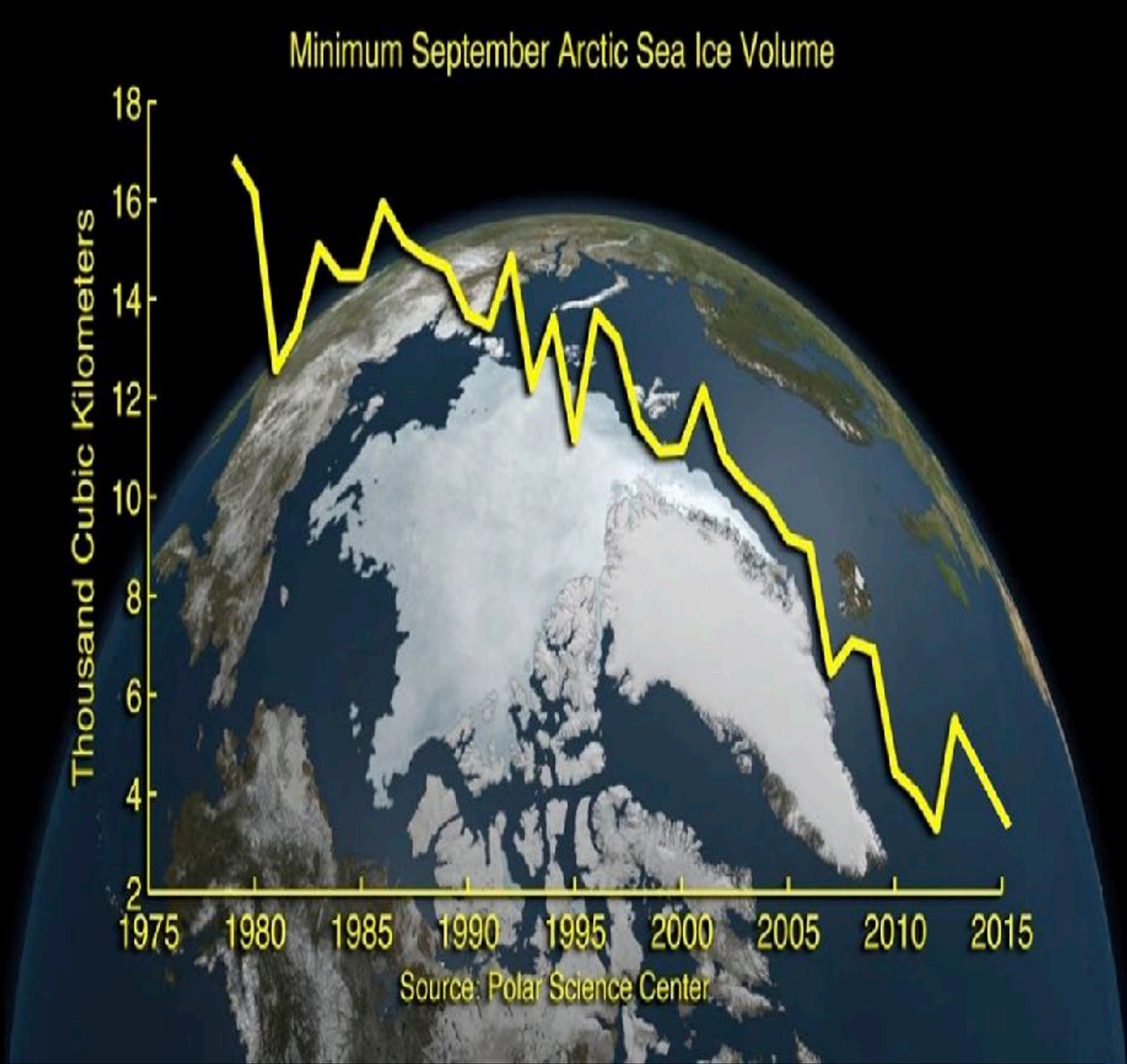
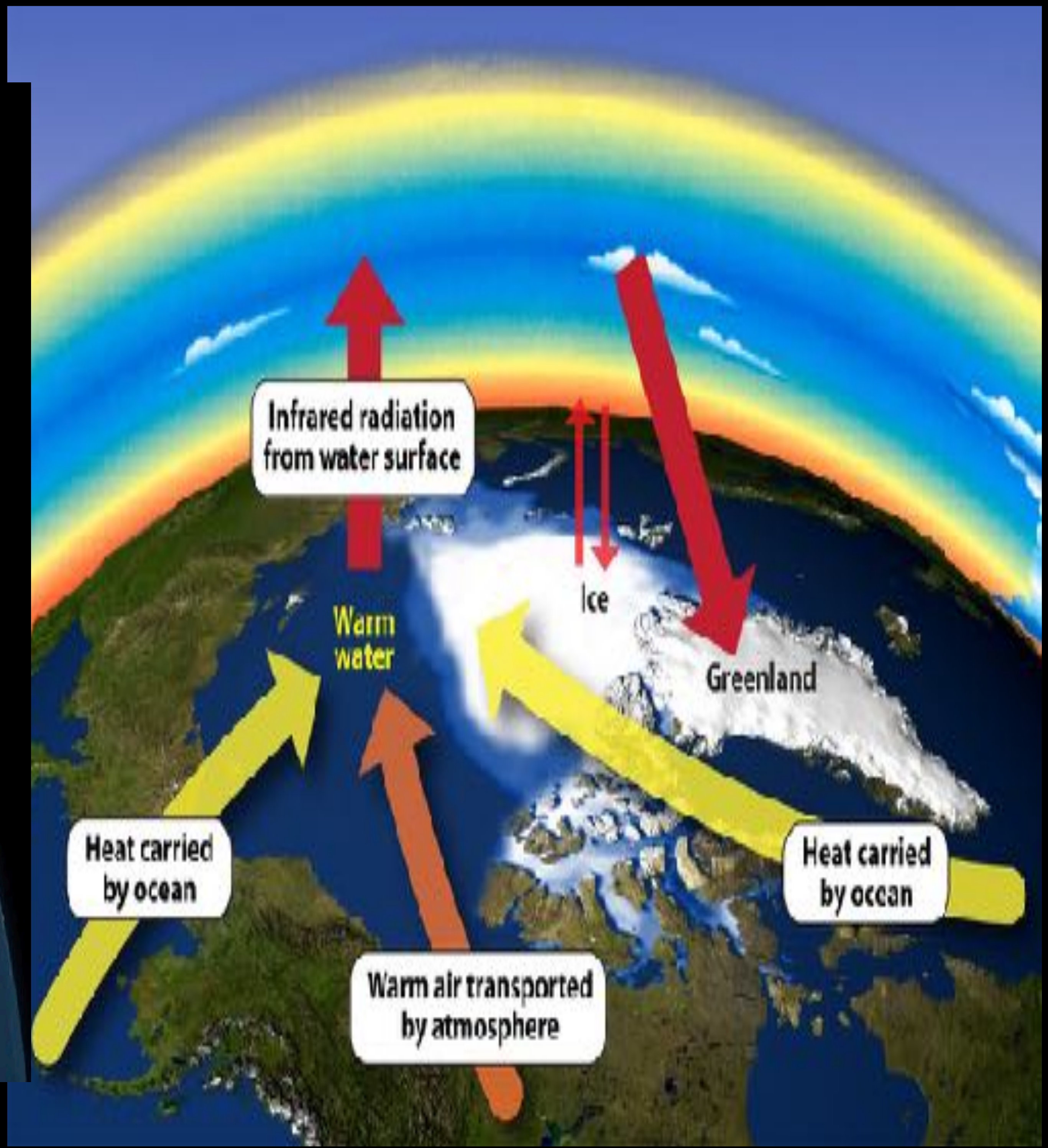


Exhibit A: Rapid Loss of “Permanent” Arctic Floating Ice
[From the University of Washington Applied Physics Lab]



Can Earth lose 75-80% of its "permanent" Arctic ice mass in thirty five years and return to a stable condition?





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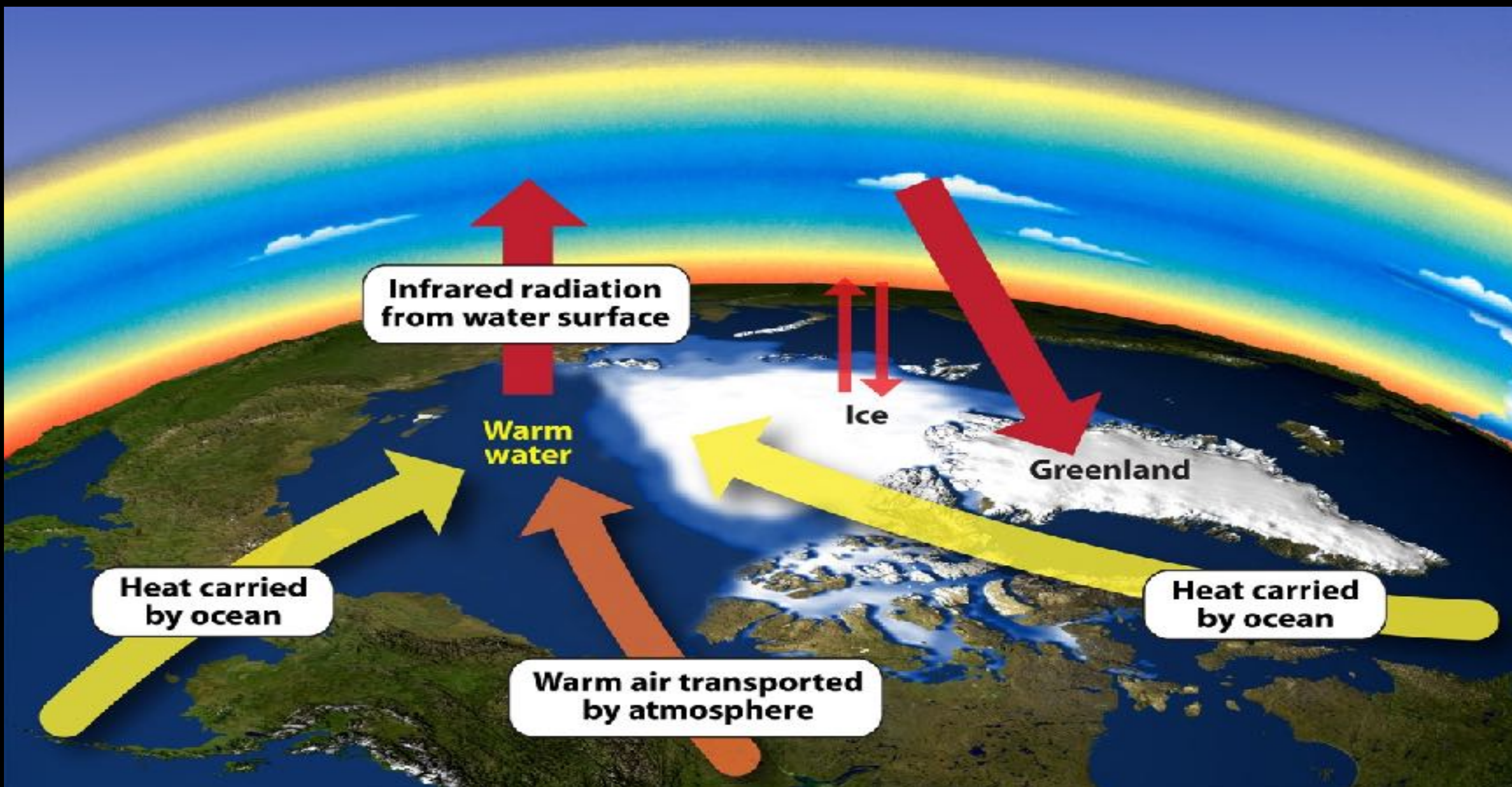
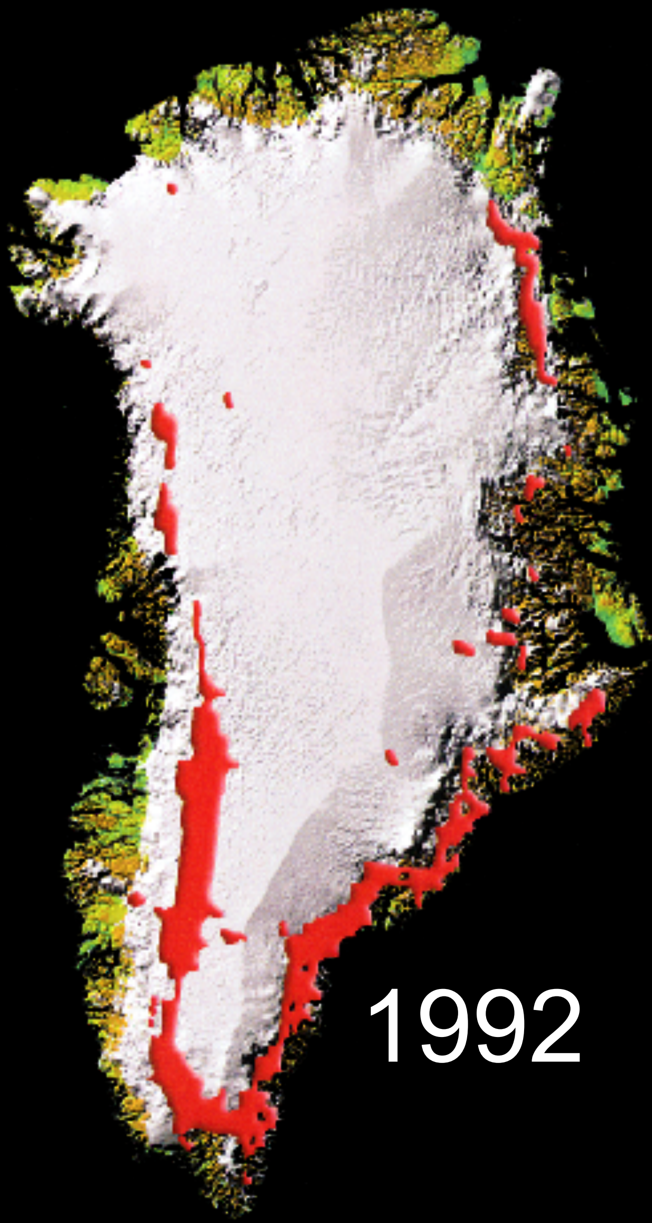
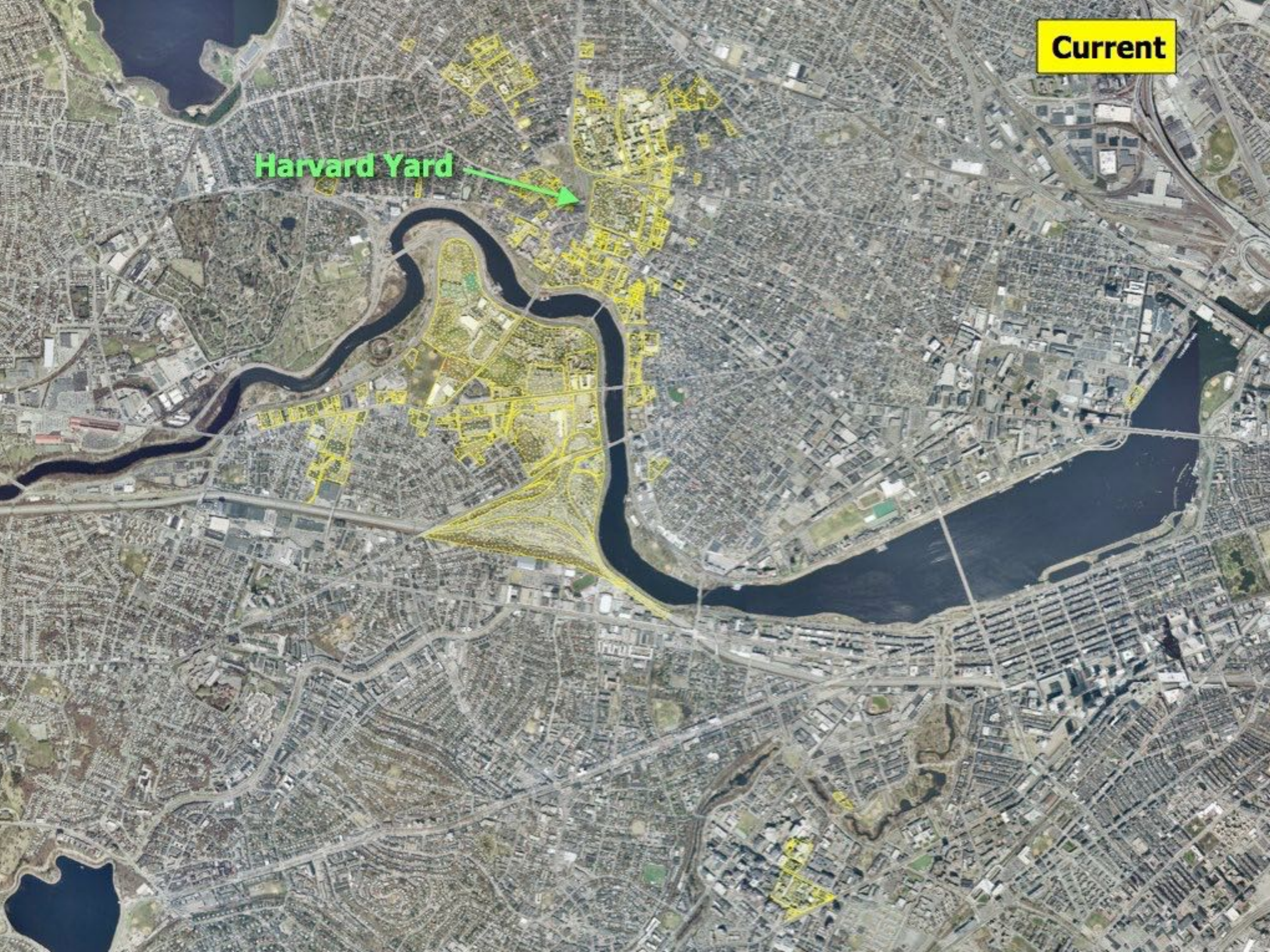


1992 2002 2005 2012

Greenland

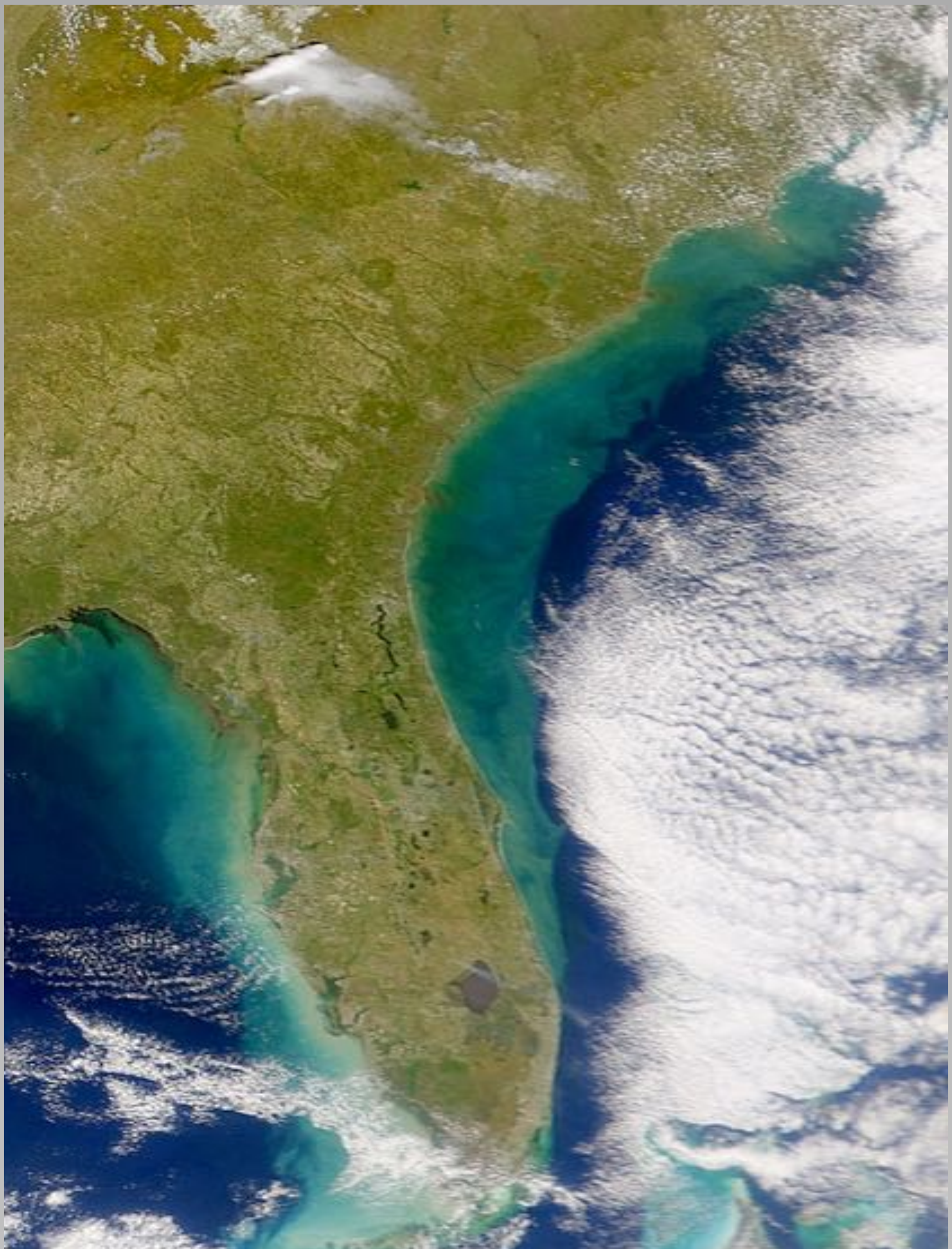


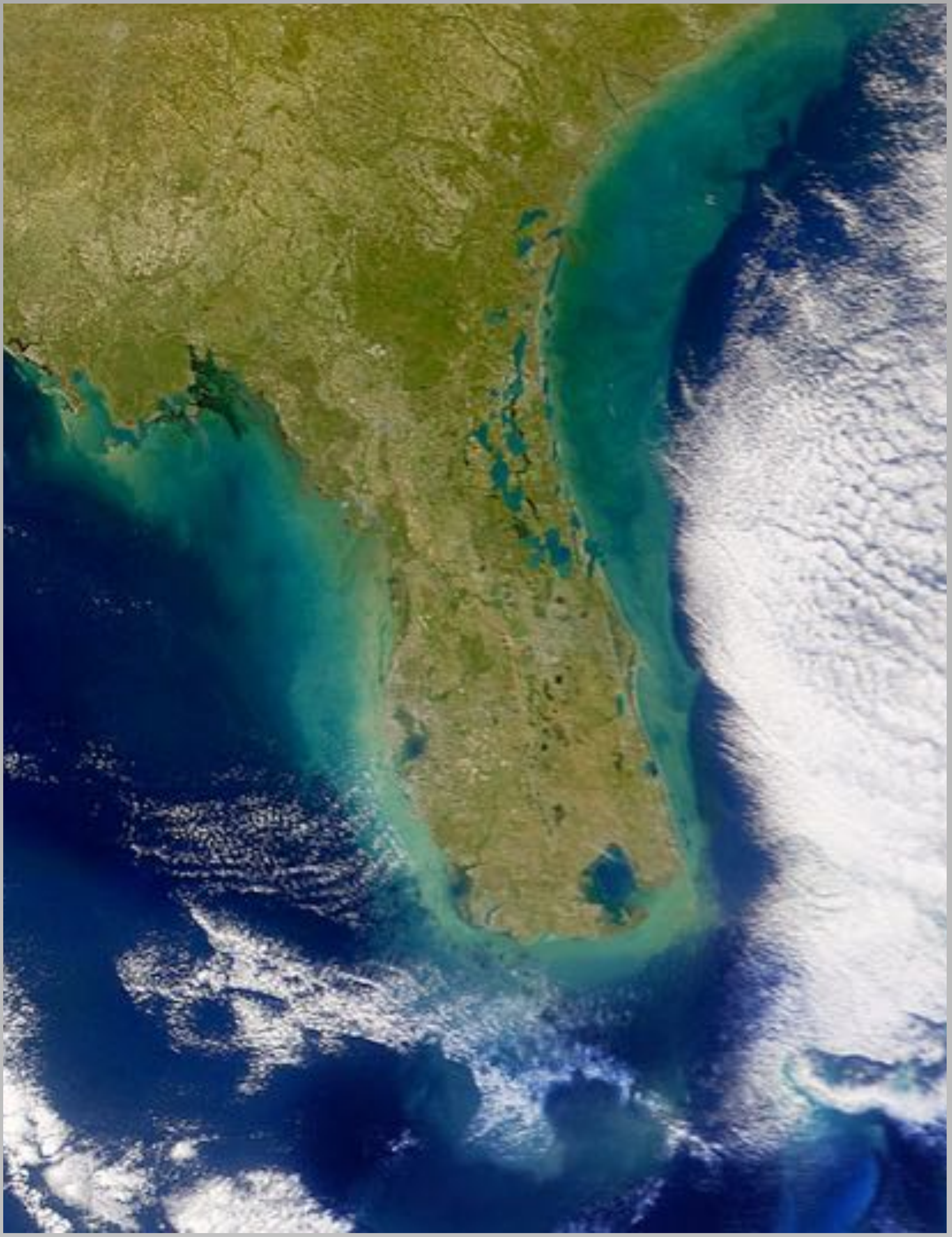


Current
Harvard Yard


1 m rise


3 m rise

Florida





S&P: Banks that ignore climate risk face credit downgrade

Published on 06/05/2016, 11:30am

Financial institutions should prepare for "multilayered and significant impacts" of global warming, analysts warn

Financial institutions should prepare for climate risk, says ratings agency (Flickr/barnyz)

By Megan Darby

269 Shares

Bloomberg climate taskforce to target financial filings

53 Shares

Published on 01/04/2016, 1:13pm

Companies should report their climate risk exposure to avoid legal issues faced by Peabody and Exxon, says lead analyst

Former New York mayor and financial data baron Michael Bloomberg is leading a climate risk task force (Pic: US Navy)

By Megan Darby

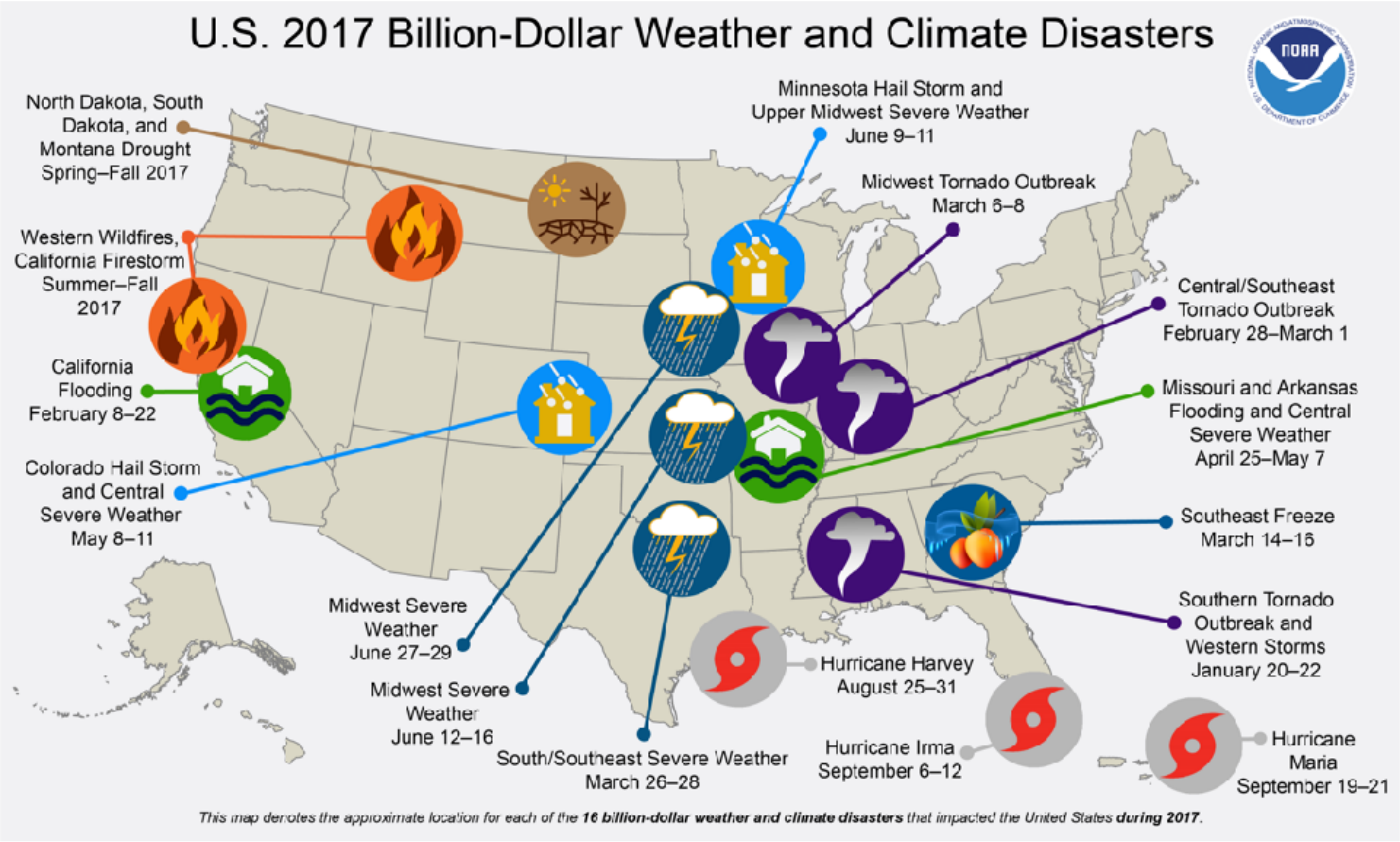
Bloomberg | Moody's Warns Cities to Address Climate Risks or Face Downgrades

Moody's Warns Cities to Address Climate Risks or Face Downgrades

By **Christopher Flavelle**
November 29, 2017, 4:00 AM EST
From **Climate Changed**

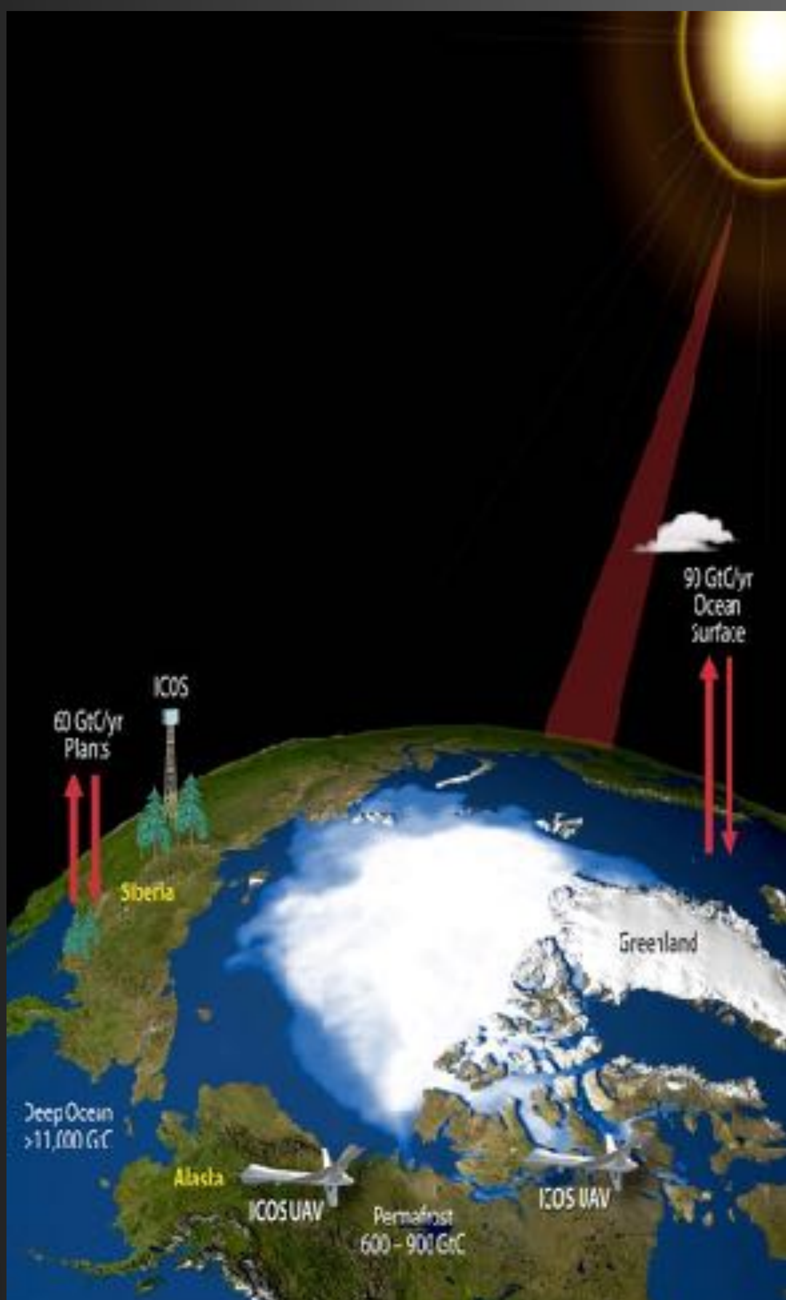
Coastal communities from Maine to California have been put on notice from one of the top credit rating agencies: Start preparing for climate change or risk losing access to cheap credit.

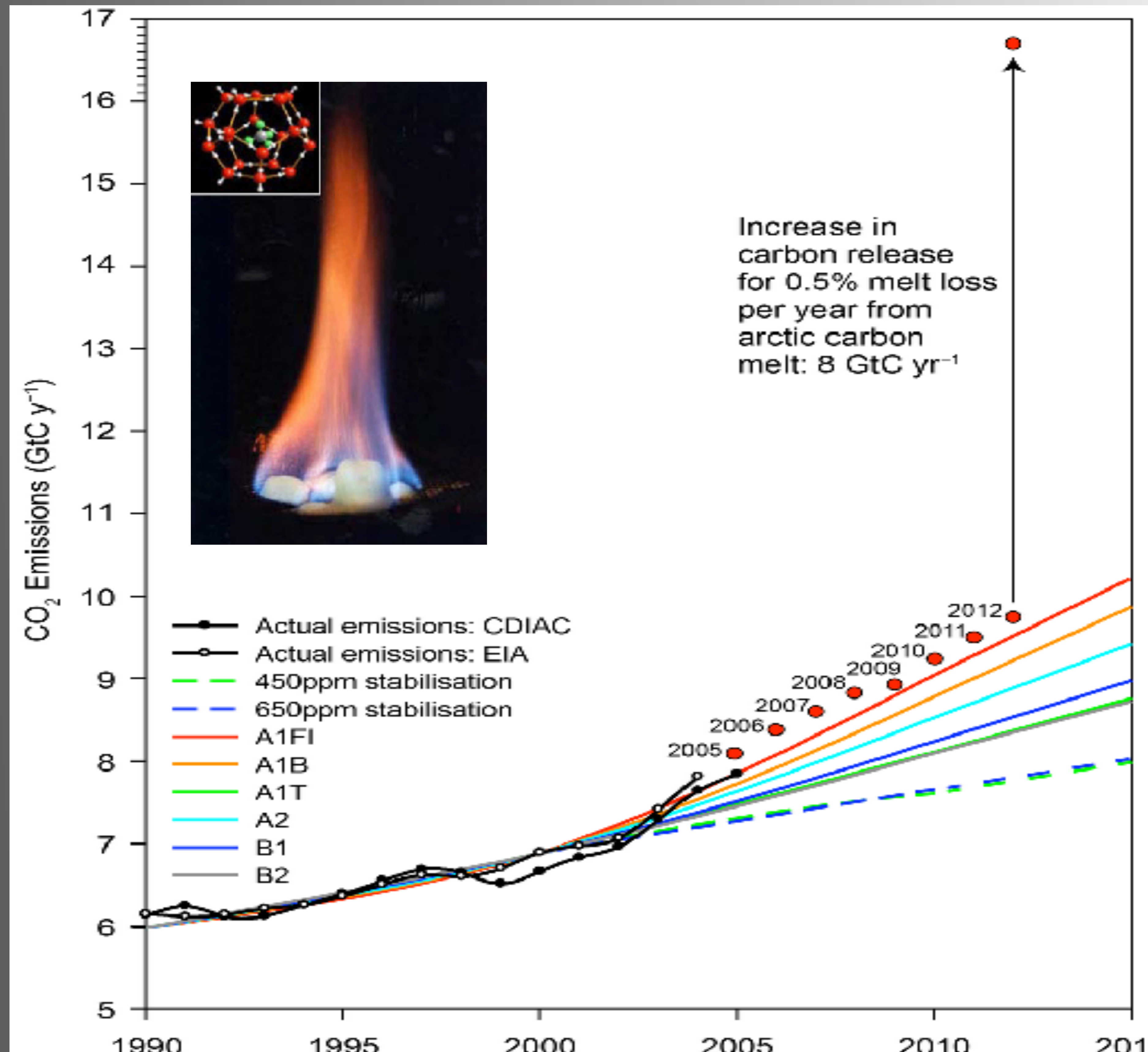
2017 Damages: $310 billion



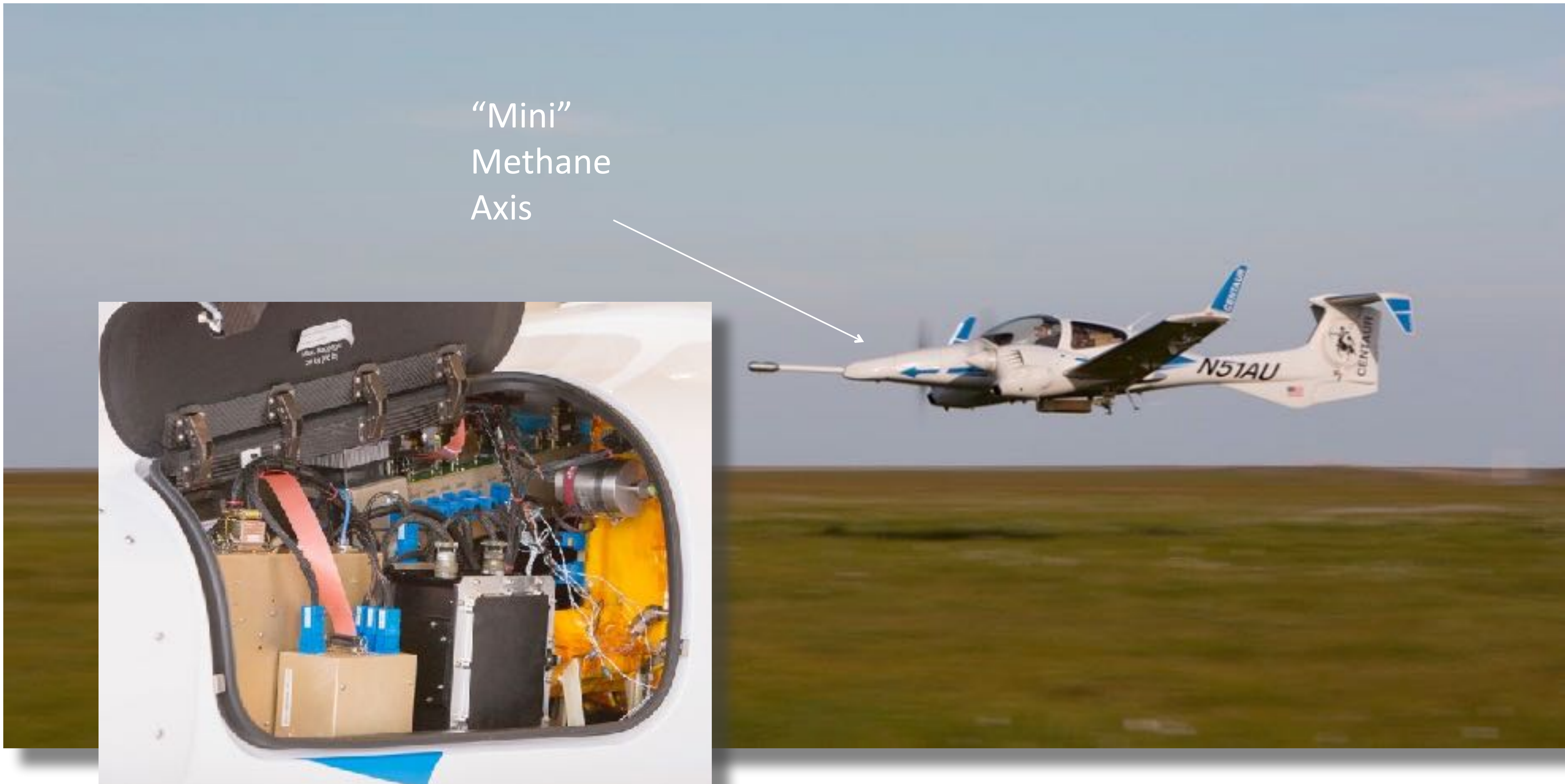
https://www.ncdc.noaa.gov/billions/

Key Feedbacks in the Climate System, Continued

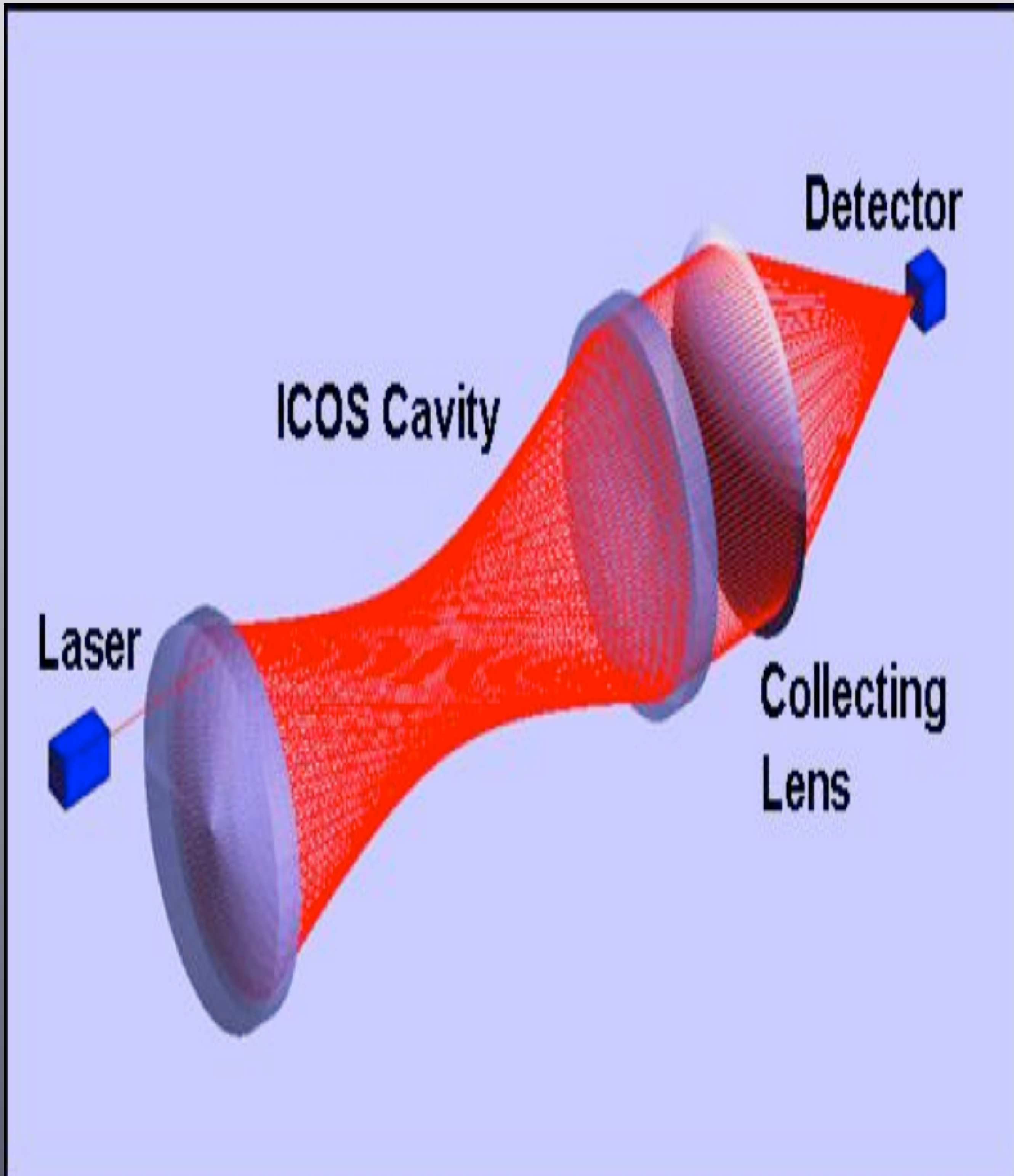


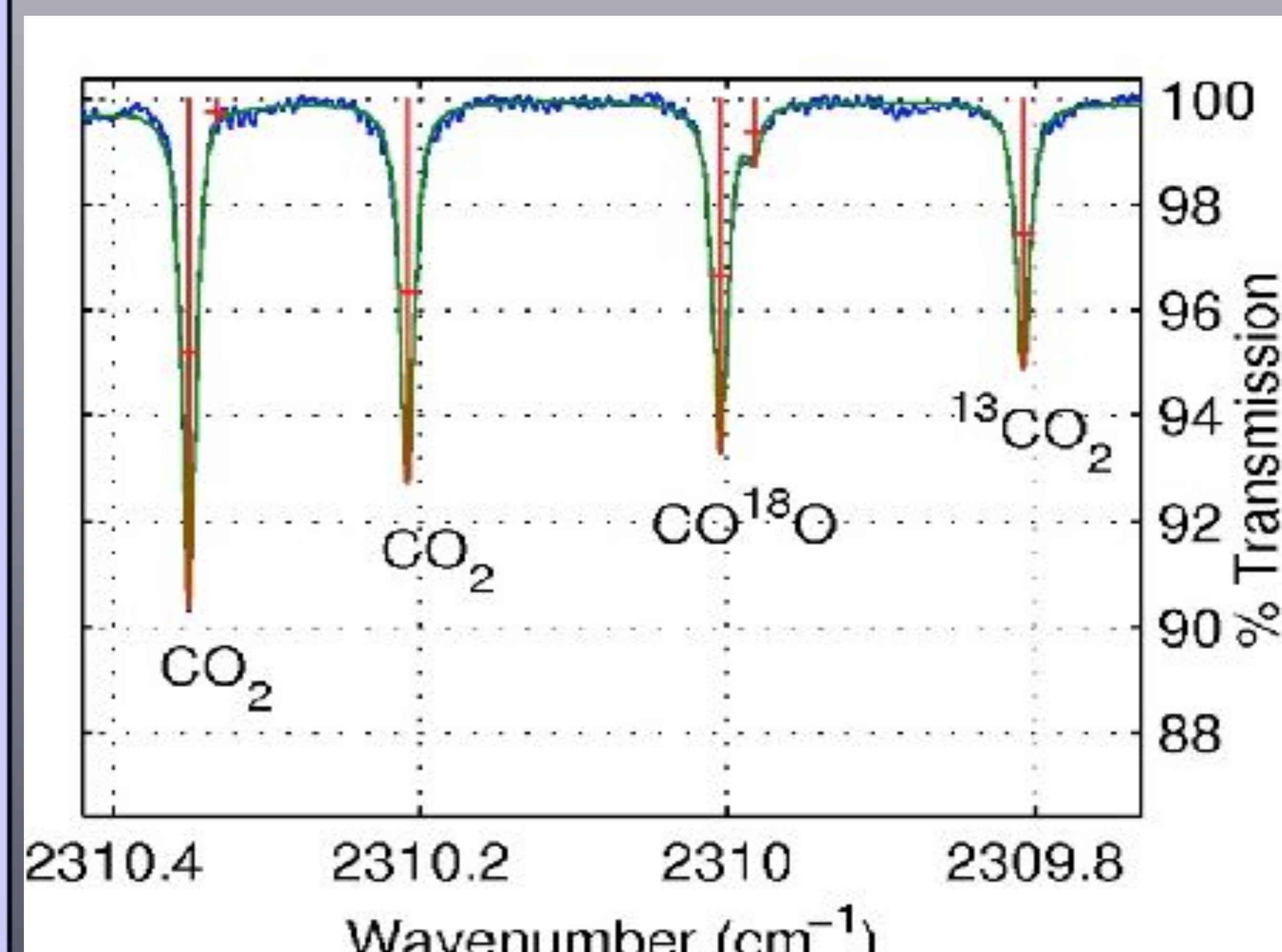


Flux Observations of Carbon Airborne Laboratory (FOCAL) System



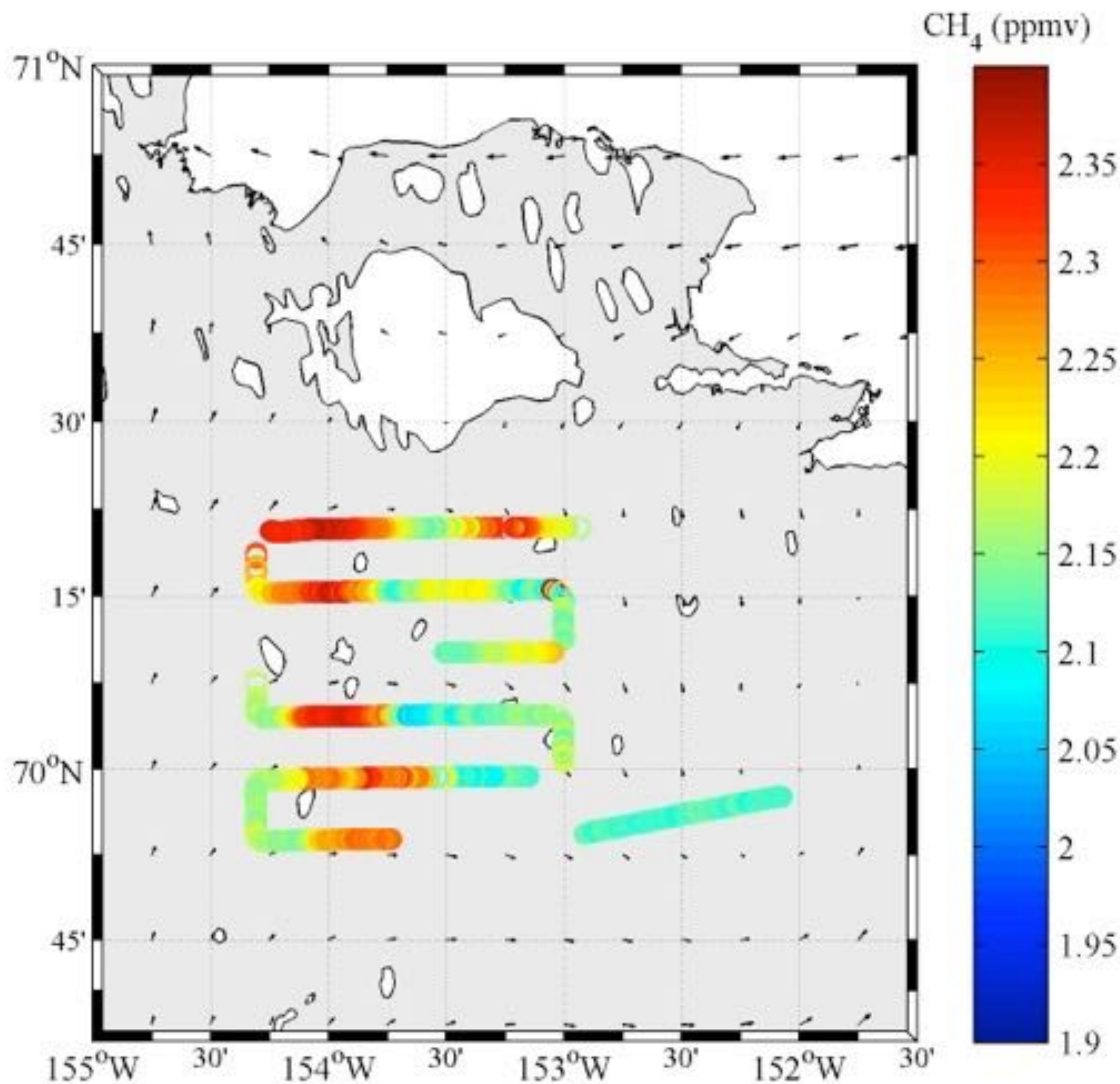
Integrated Cavity Output Spectroscopy



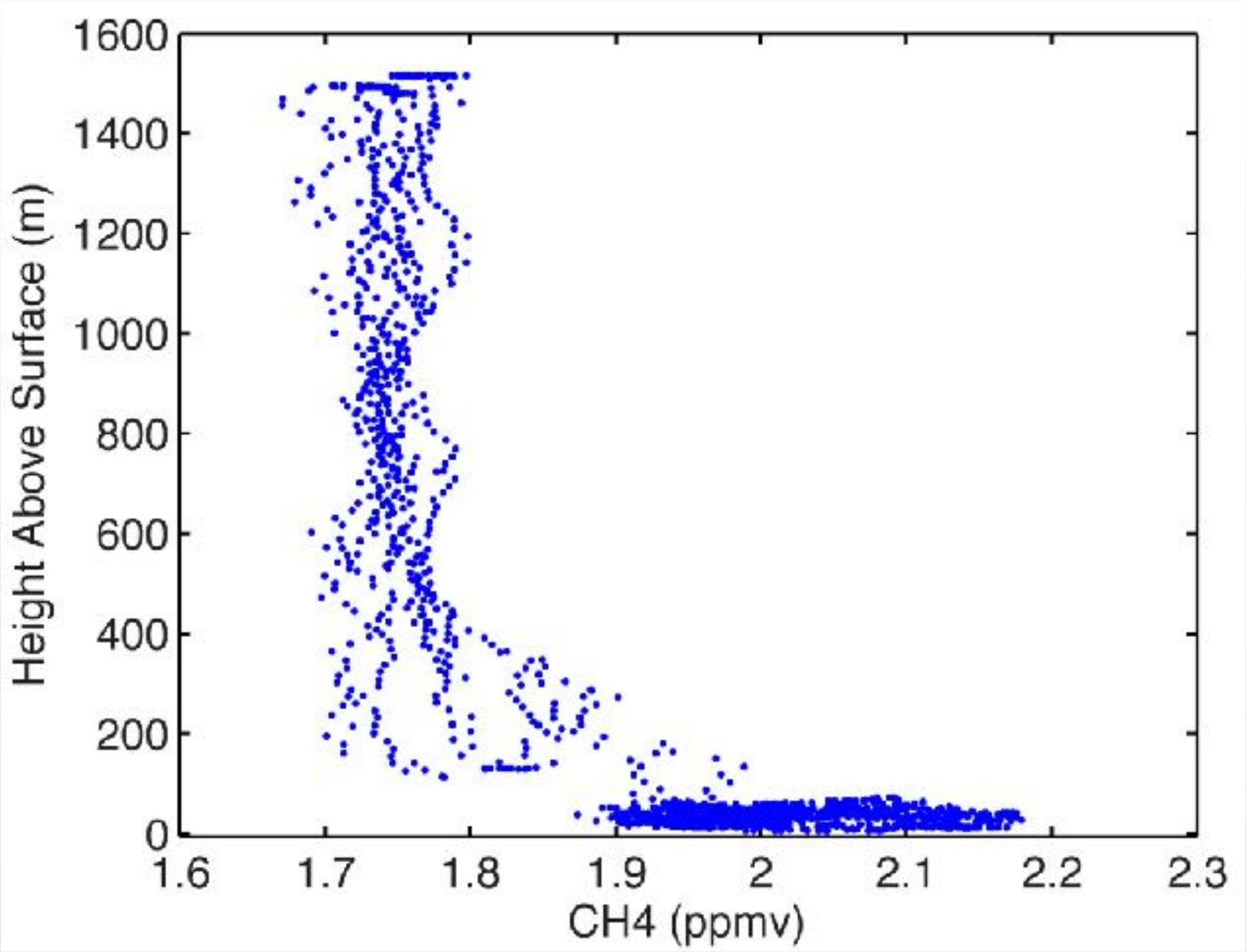


The Ability to Fly Close Tolerance is Critical for High Spatial Resolution Observations

Conclusions From North Slope Deployment: High Spatial Resolution is Critically Important

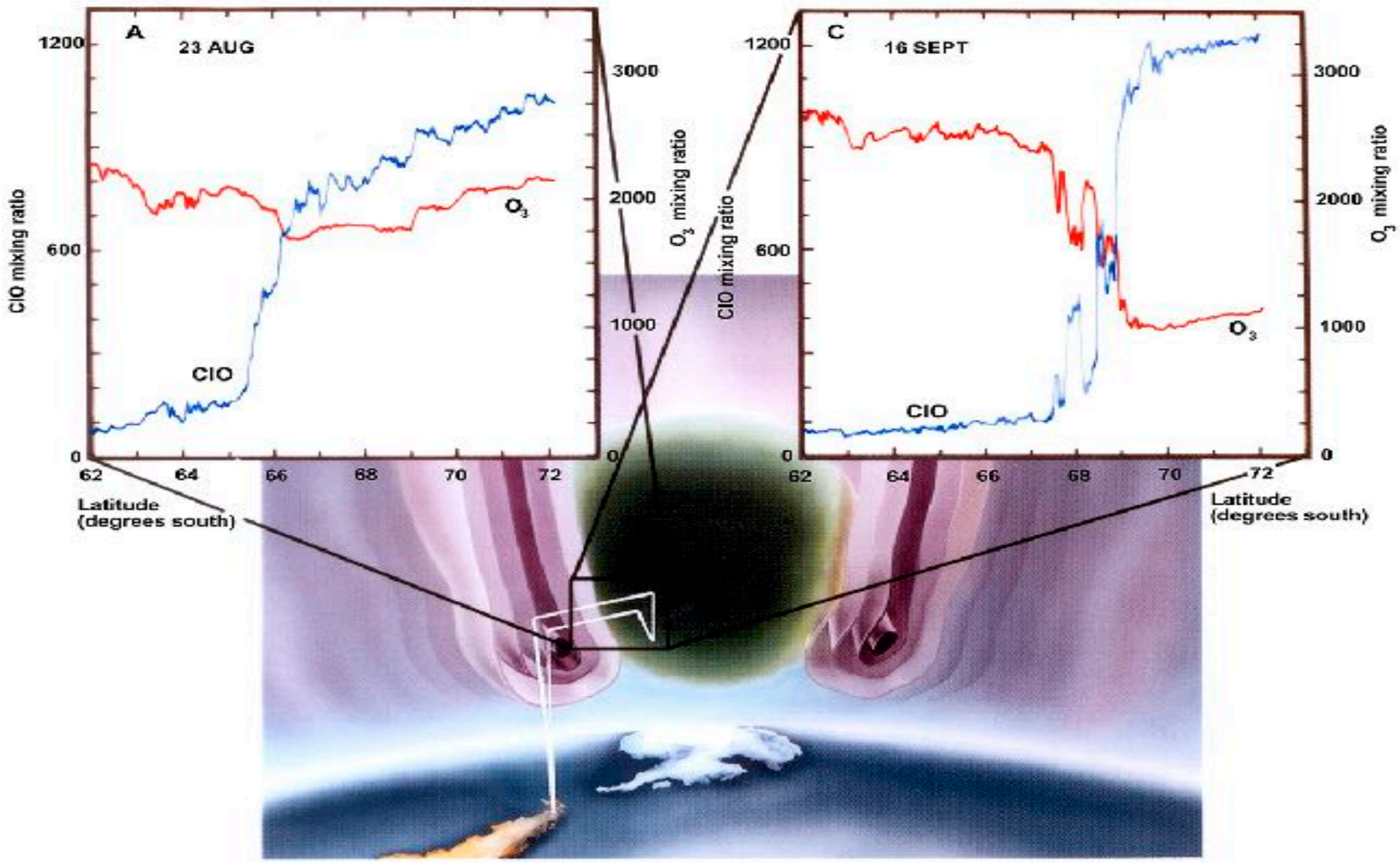


Vertical Profile of CH_4



The altitude dependence of the CH_4 mixing ratio in ppmv that displays the large dynamic range of the mixing ratio in the very lowest part of the boundary layer.

Close to Home: What Does Climate Change Have to Do With Stratospheric Ozone Over the Central US in Summer?



A
23 AUG
C
16 SEPT
ClO mixing ratio
O_3 mixing ratio
1200
600
0
3000
2000
1000
ClO
O_3
62
64
66
68
70
72
Latitude (degrees south)

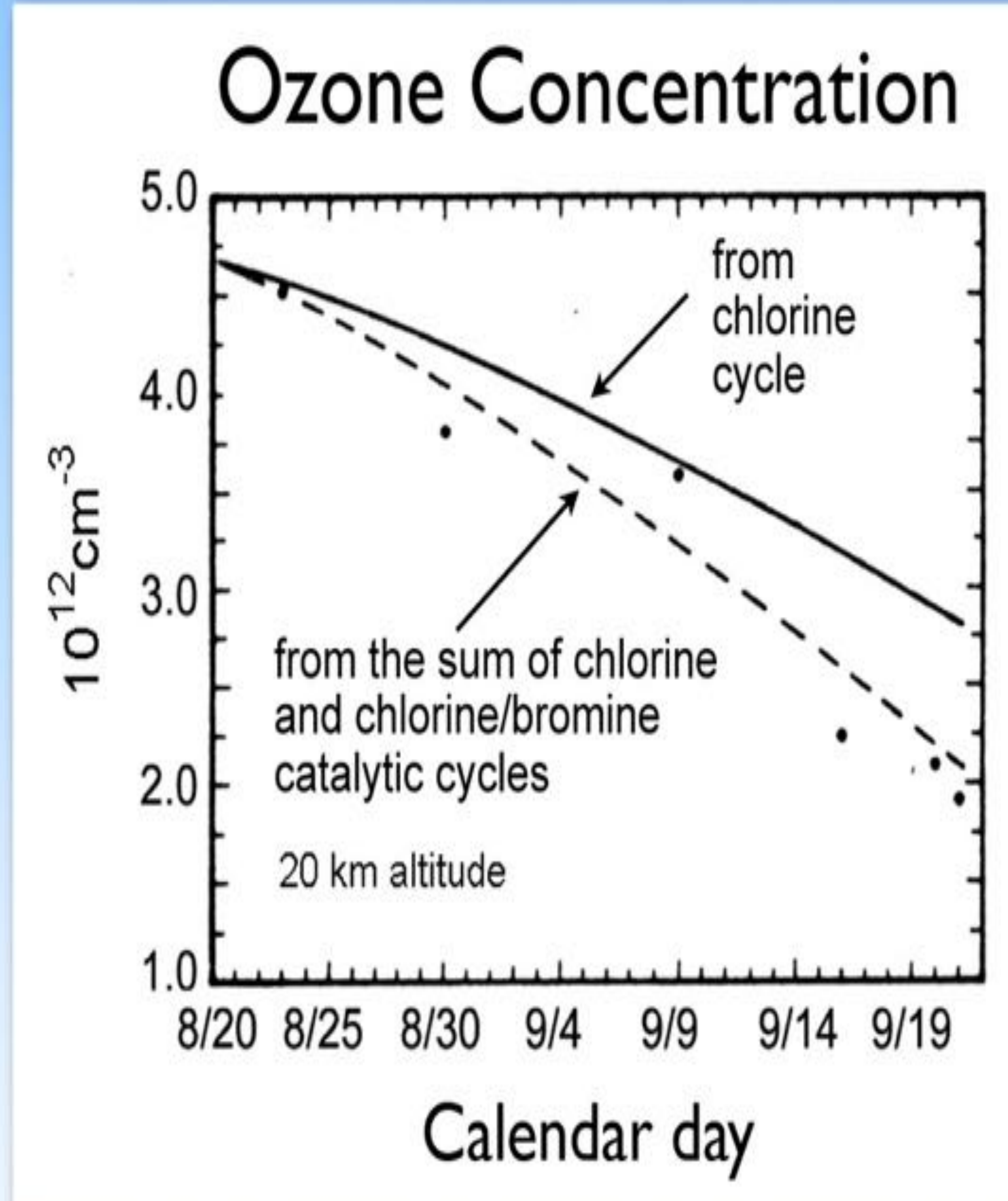
$$RLS \quad ClO + ClO + M \rightarrow ClOOCl + M$$

$$ClOOCl + h\nu \rightarrow Cl + ClOO$$

$$ClOO + M \rightarrow Cl + O_2 + M$$

$$2 \times \left(Cl + O_3 \rightarrow ClO + O_2\right)$$

$$\text{Net:} \quad O_3 + O_3 \rightarrow 3O_2$$



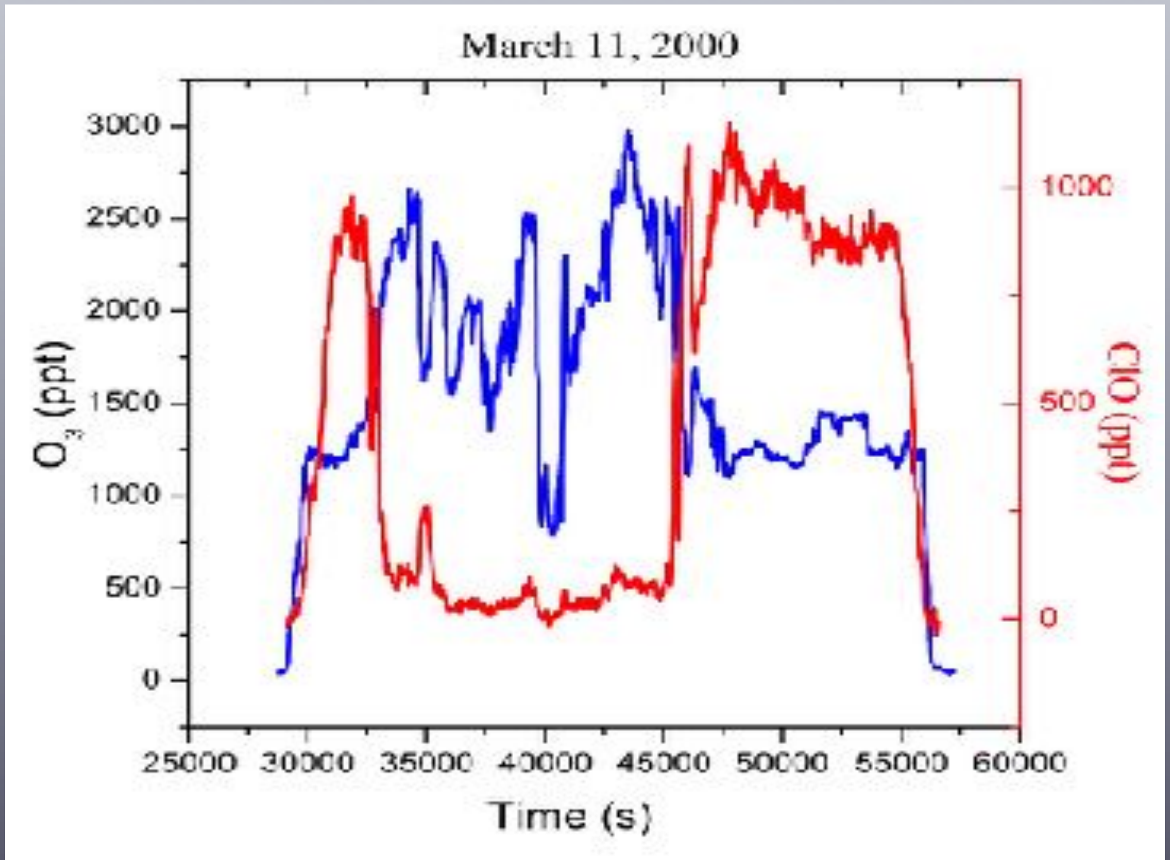
$$RLS \quad ClO + BrO \rightarrow Cl + Br + O_2$$

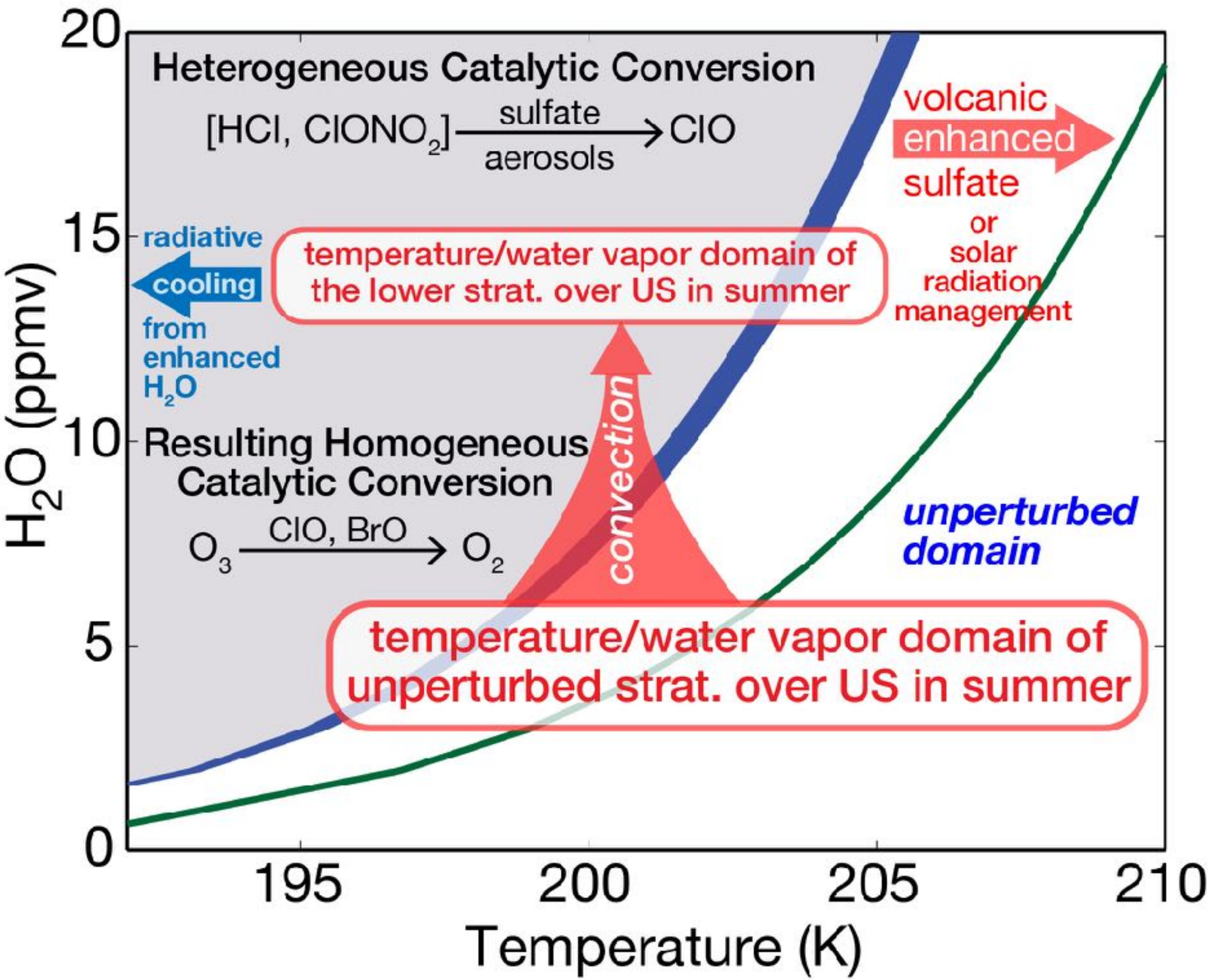
$$Cl + O_3 \rightarrow ClO + O_2$$

$$Br + O_3 \rightarrow BrO + O_2$$

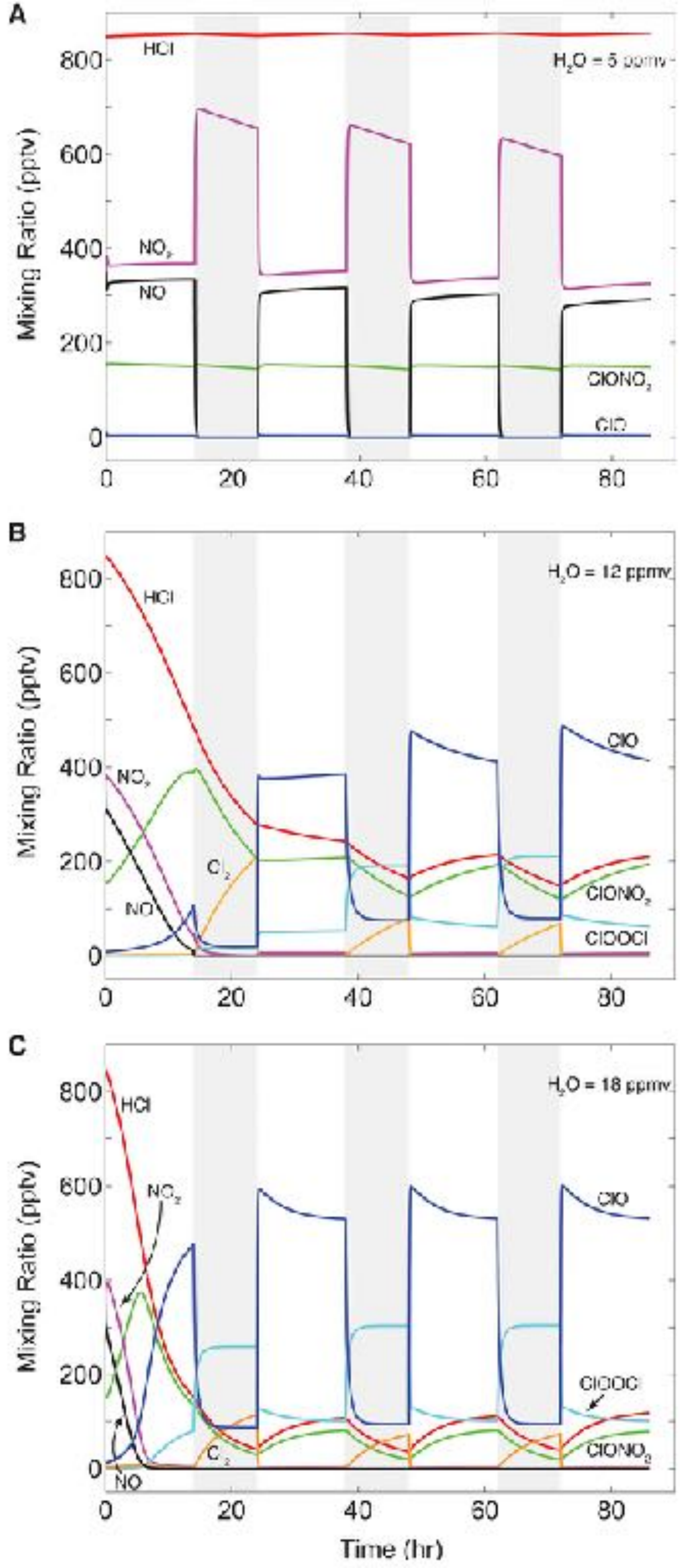
$$\text{Net:} \quad O_3 + O_3 \rightarrow 3O_2$$

But What About the Arctic?





Heterogeneous Catalytic Conversion
[HCl, ClONO2] sulfate aerosols → ClO
volcanic
enhanced
sulfate
or
solar
radiation
management
radiative
cooling
from
enhanced
H2O
temperature/water vapor domain of
the lower strat. over US in summer
Resulting Homogeneous
Catalytic Conversion
O3 ClO, BrO → O2
convection
unperturbed
domain
temperature/water vapor domain of
unperturbed strat. over US in summer
H2O (ppmv)
Temperature (K)
0
5
10
15
20
195
200
205
210



$$\mathit{RLS} \quad ClO + ClO + M \rightarrow ClOOCl + M$$

$$ClOOCl + h\nu \rightarrow Cl + ClOO$$

$$ClOO + M \rightarrow Cl + O_2 + M$$

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$$\mathit{RLS} \quad ClO + BrO \rightarrow Cl + Br + O_2$$

$$Cl + O_3 \rightarrow ClO + O_2$$

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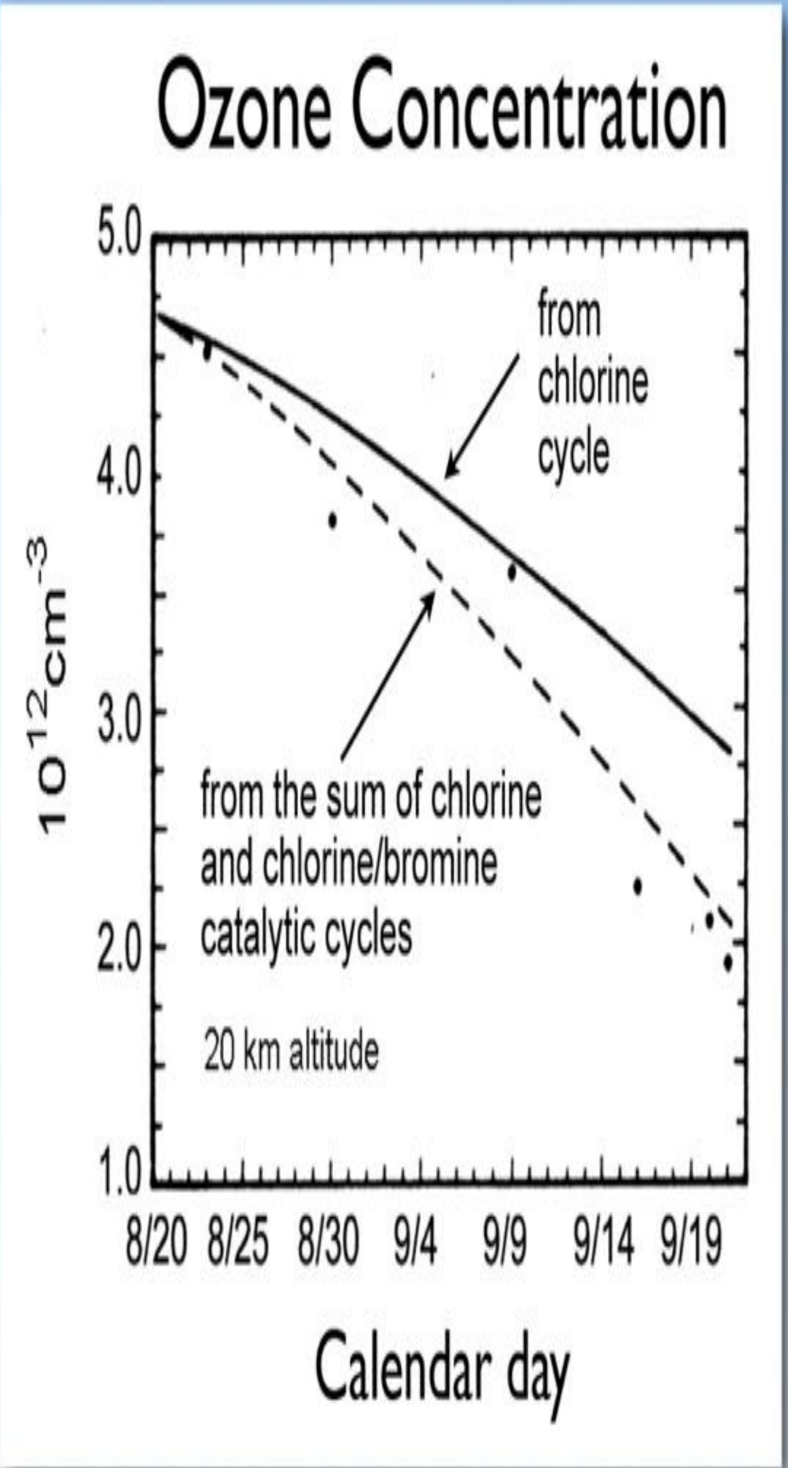
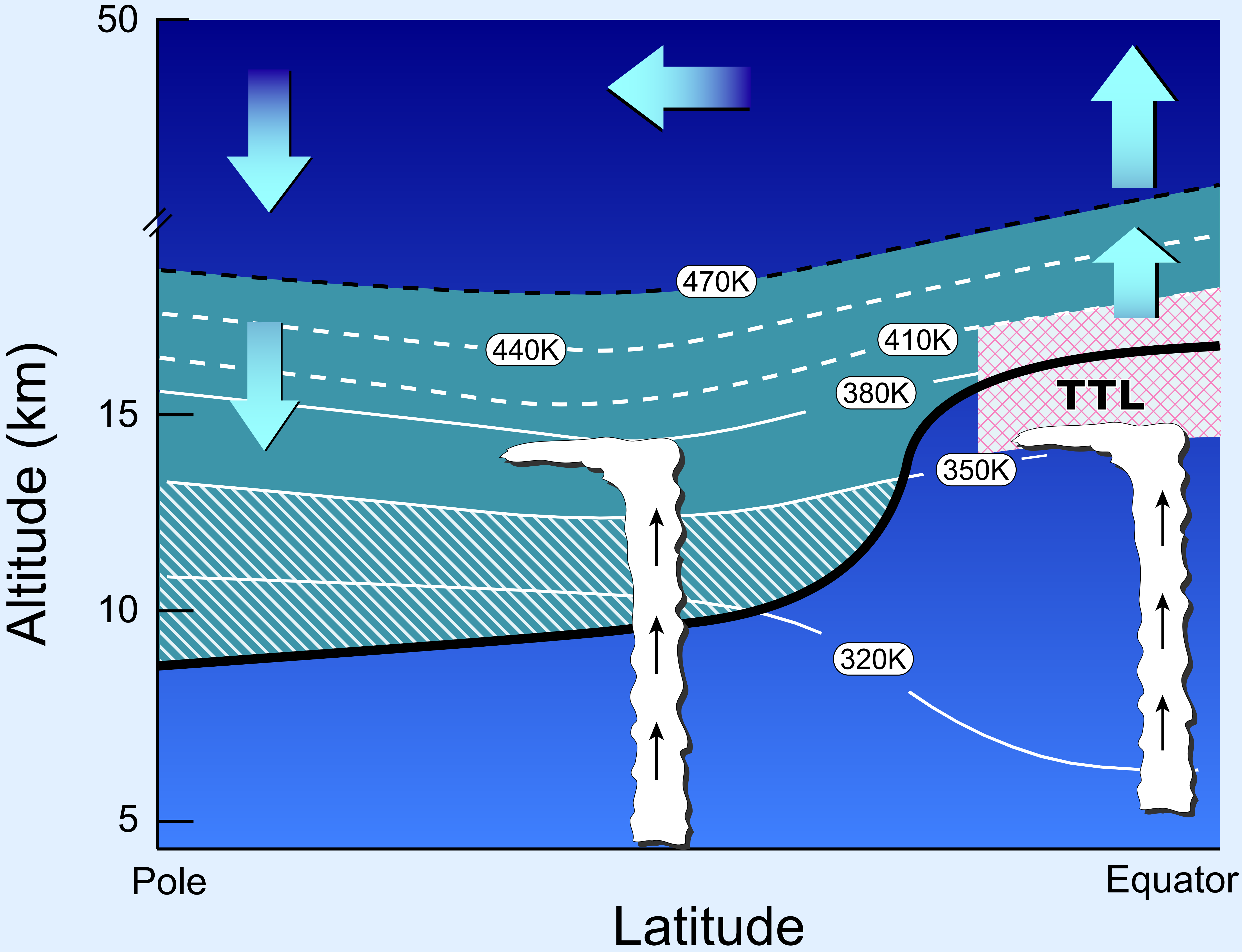
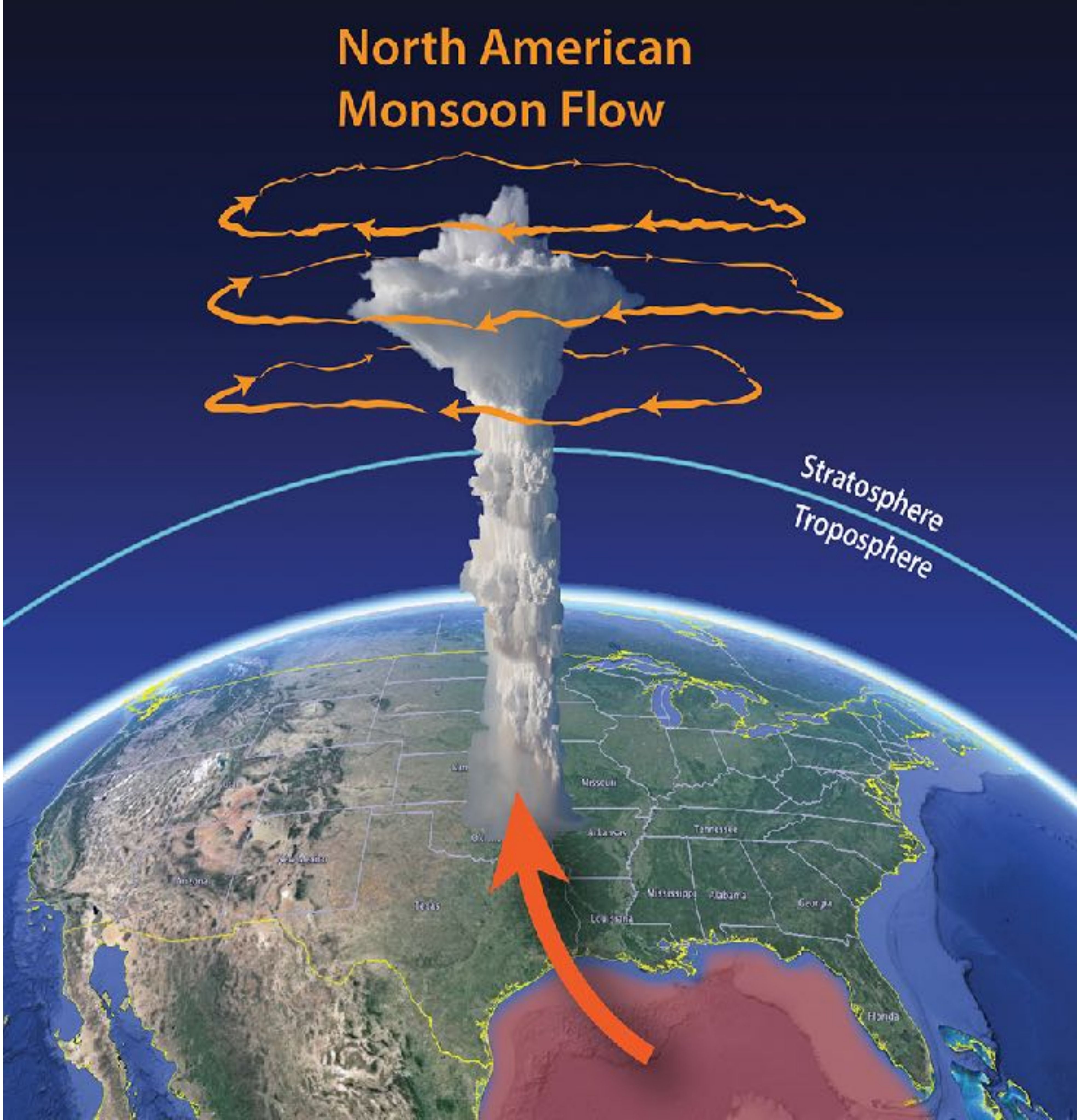
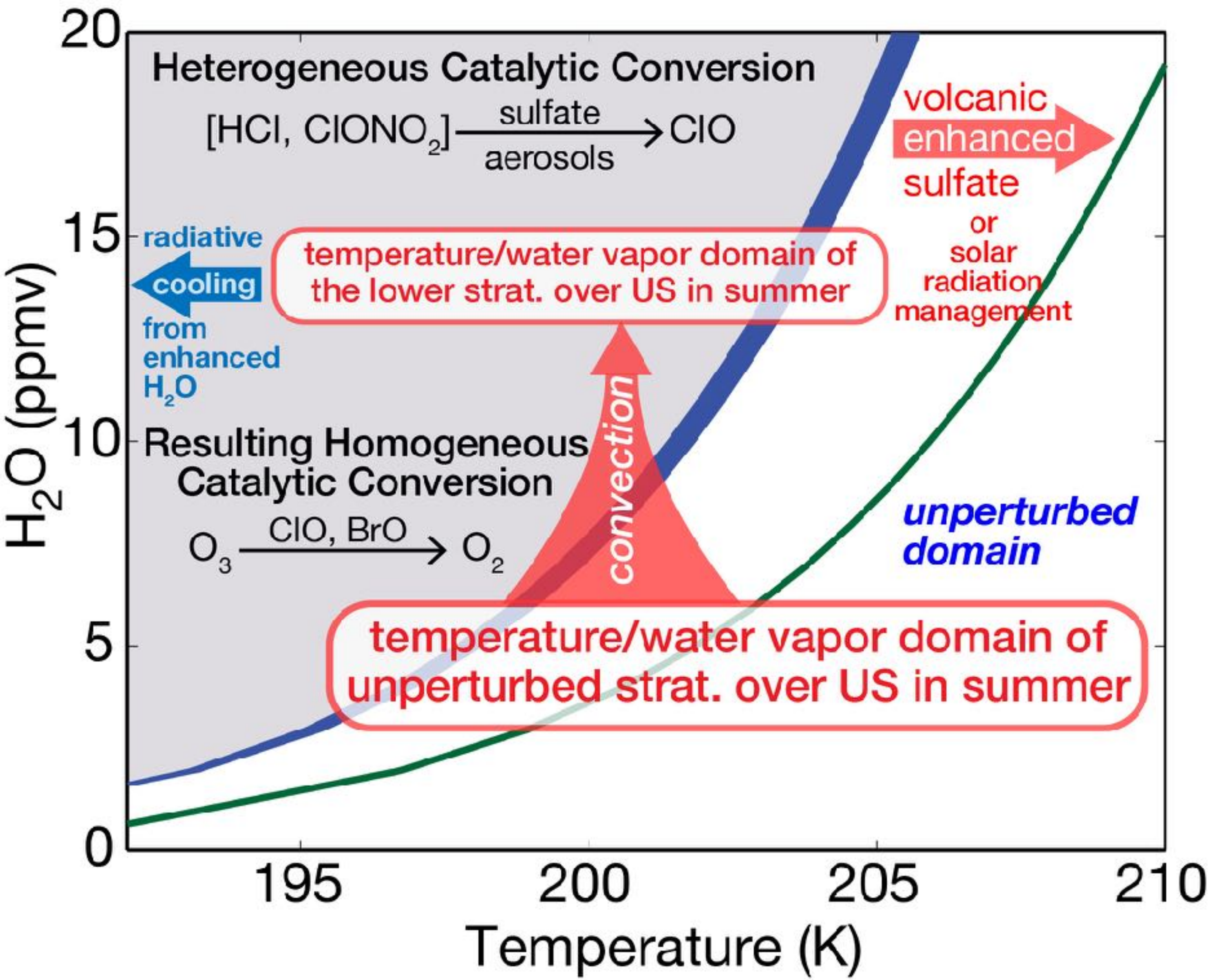


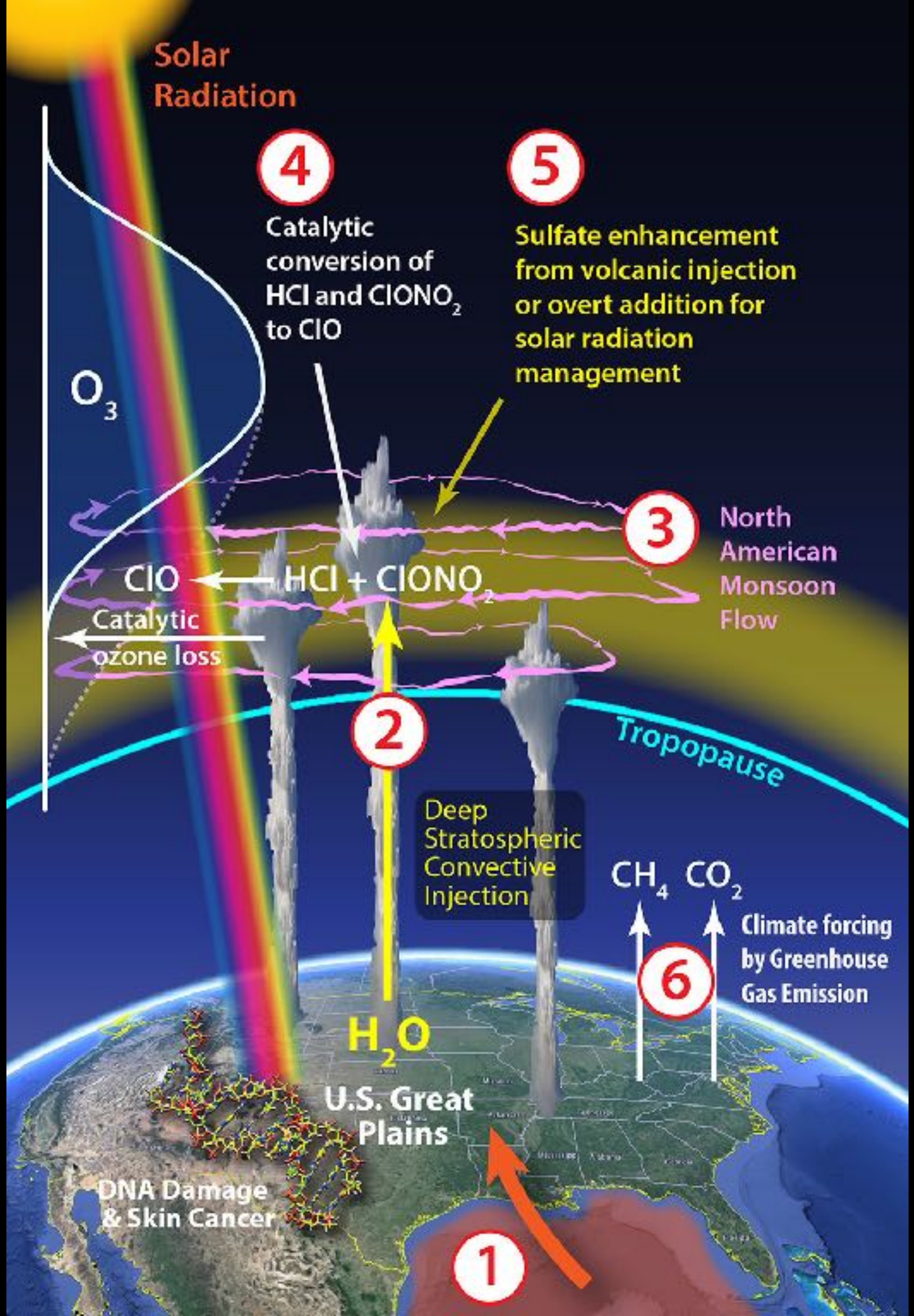
Research Shifted to Investigations of How Storm Systems Affect Climate Change



50
15
10
5
Altitude (km)
470K
440K
410K
380K
350K
320K
TTL
Pole
Equator
Latitude


North American
Monsoon Flow
Stratosphere
Troposphere
Missouri
Arkansas
Tennessee
Texas
Mississippi
Alabama
Louisiana

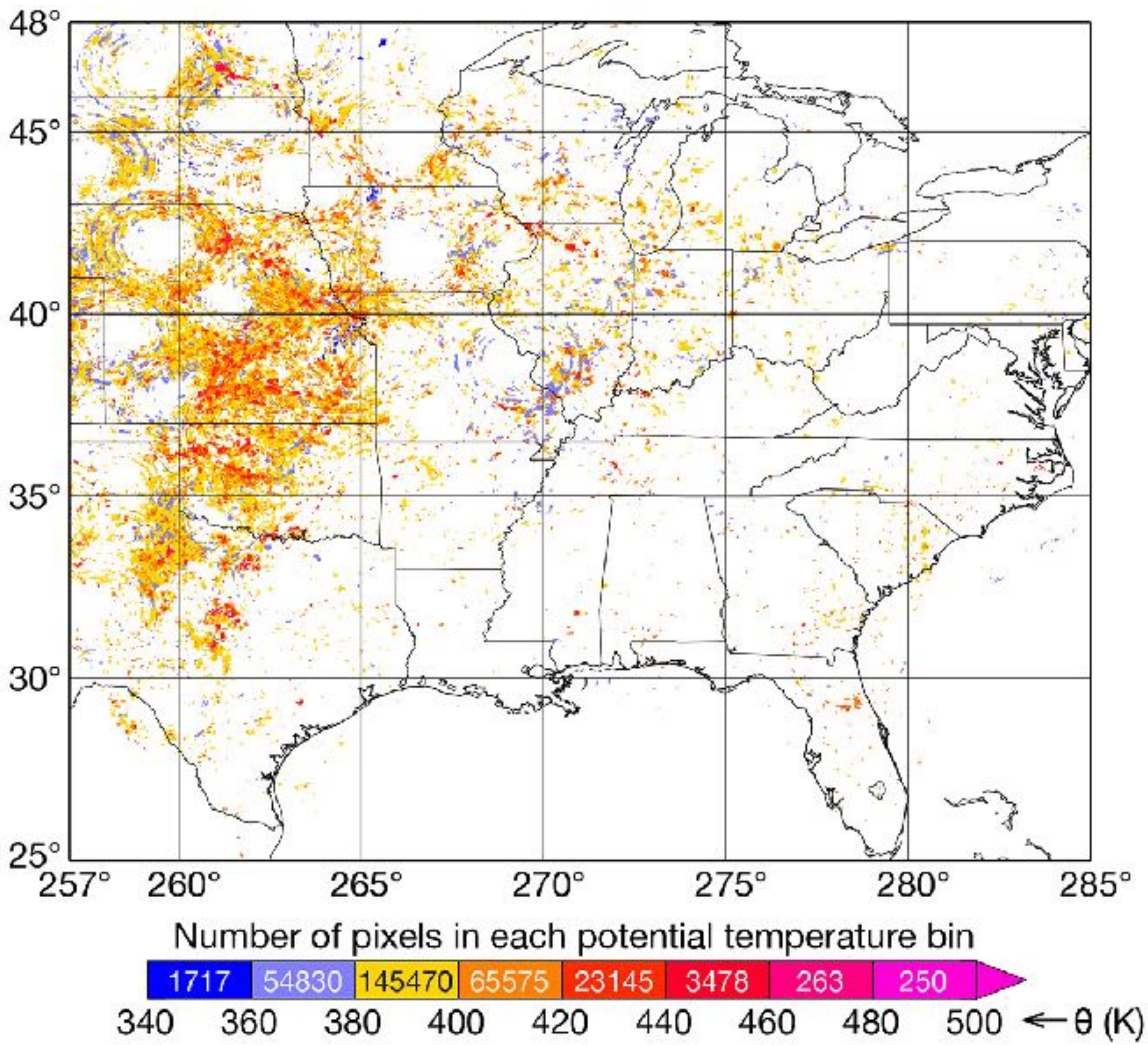

Heterogeneous Catalytic Conversion
$[HCl, ClONO_2] \xrightarrow[\text{aerosols}]{\text{sulfate}} ClO$
volcanic enhanced sulfate or solar radiation management
radiative cooling from enhanced H_2O
temperature/water vapor domain of the lower strat. over US in summer
convection
Resulting Homogeneous Catalytic Conversion
$O_3 \xrightarrow{ClO, BrO} O_2$
unperturbed domain
temperature/water vapor domain of unperturbed strat. over US in summer
H_2O (ppmv)
Temperature (K)
0
5
10
15
20
195
200
205
210

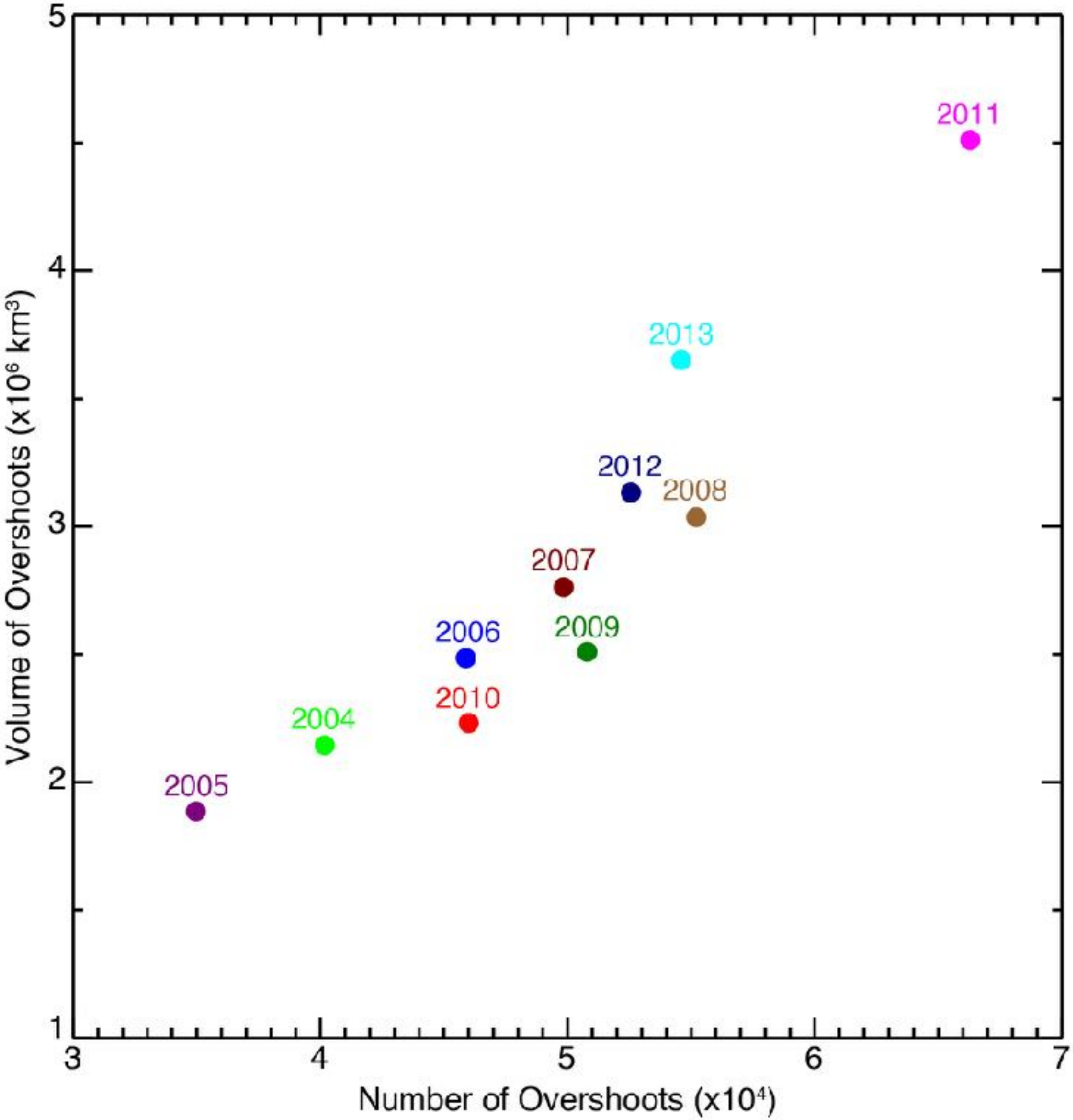


Solar Radiation
4
Catalytic conversion of HCl and $ClONO_2$ to ClO
5
Sulfate enhancement from volcanic injection or overt addition for solar radiation management
O_3
3
North American Monsoon Flow
ClO
HCl + $ClONO_2$
Catalytic ozone loss
2
Tropopause
Deep Stratospheric Convective Injection
CH_4 CO_2
6
Climate forcing by Greenhouse Gas Emission
H_2O
U.S. Great Plains
DNA Damage & Skin Cancer
1

Next Generation Weather Radar: *NEXRAD*

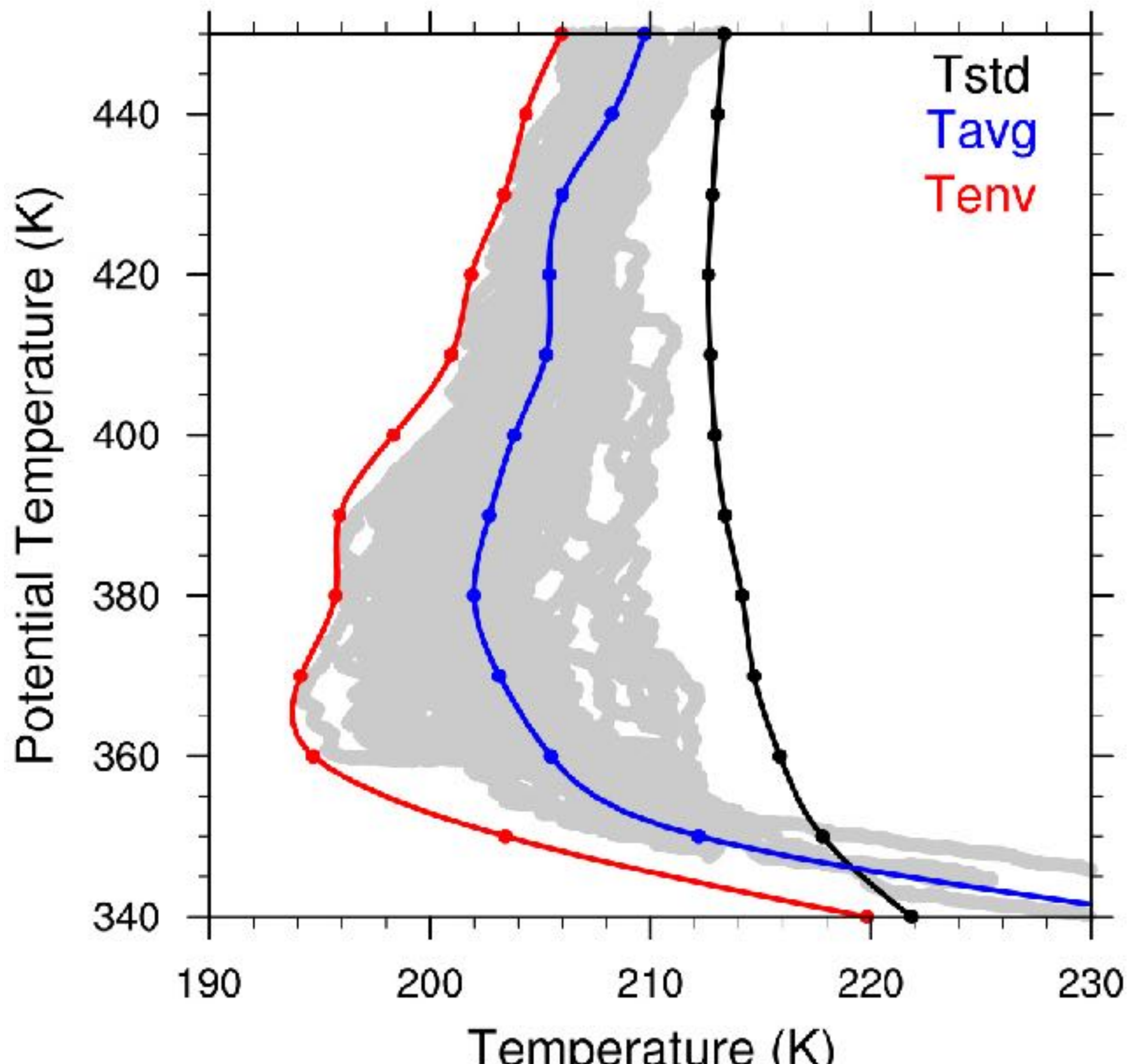
Ken Bowman Texas A&M and Cameron Homeyer Univ. of Oklahoma



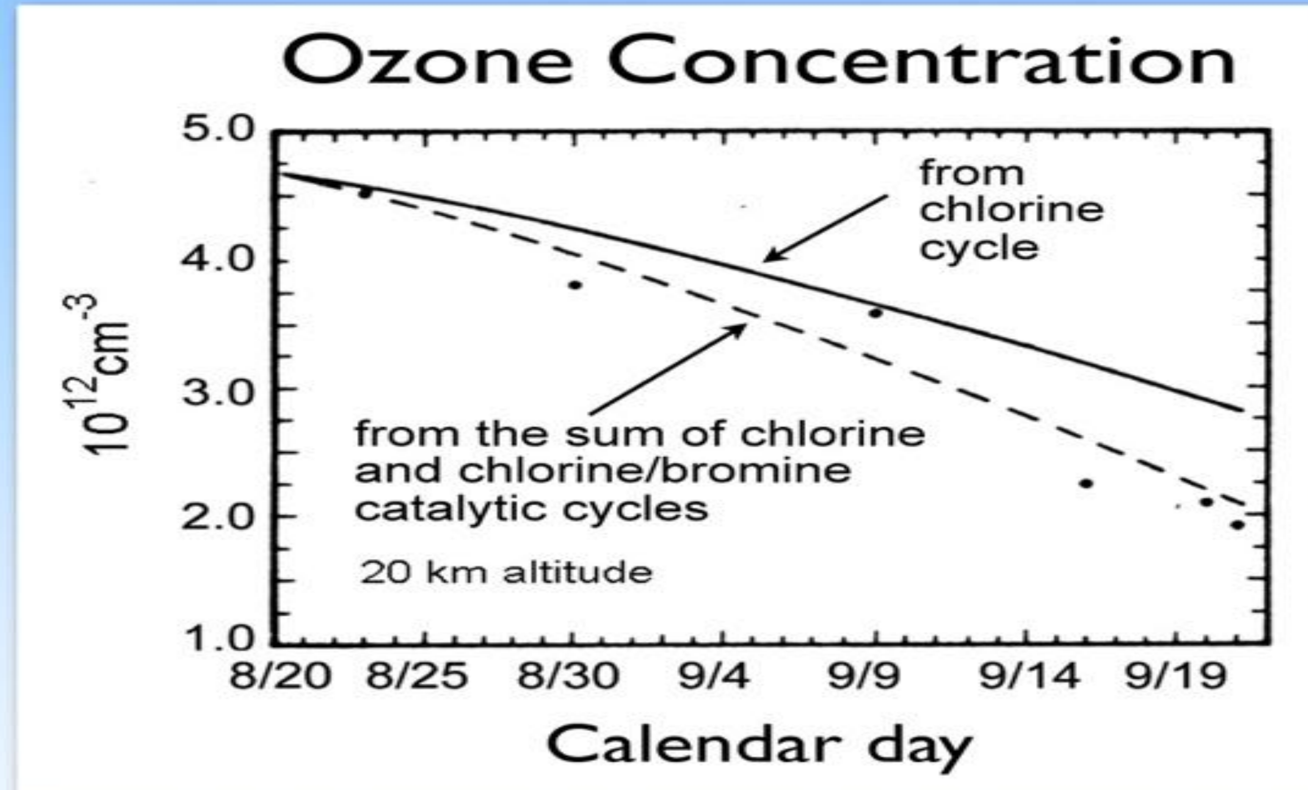


2011
2013
2012
2008
2007
2006
2009
2010
2004
2005
5
4
3
2
1
3
4
5
6
7
Volume of Overshoots (x10^6 km^3)
Number of Overshoots (x10^4)

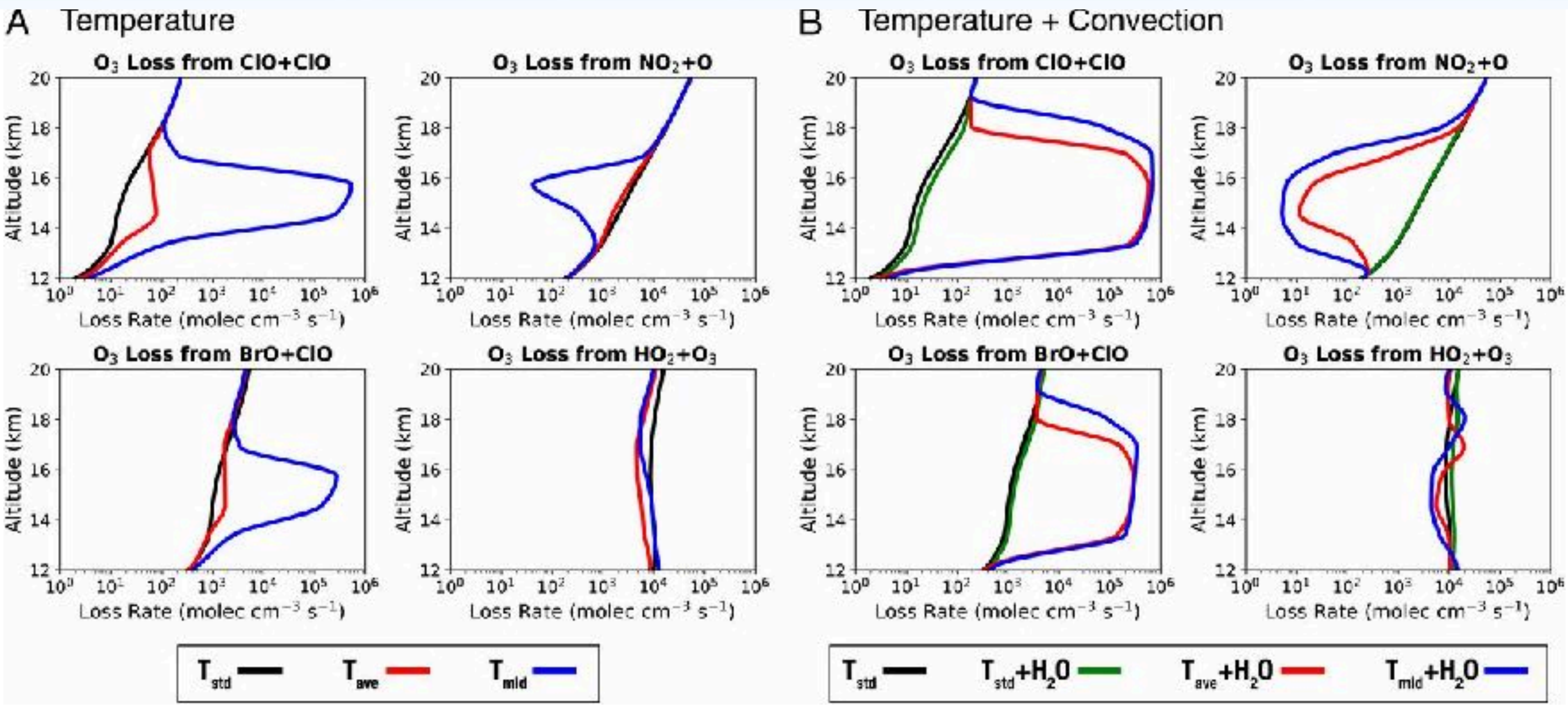
High Accuracy, High Spatial Resolution *In Situ* Temperature Measurements

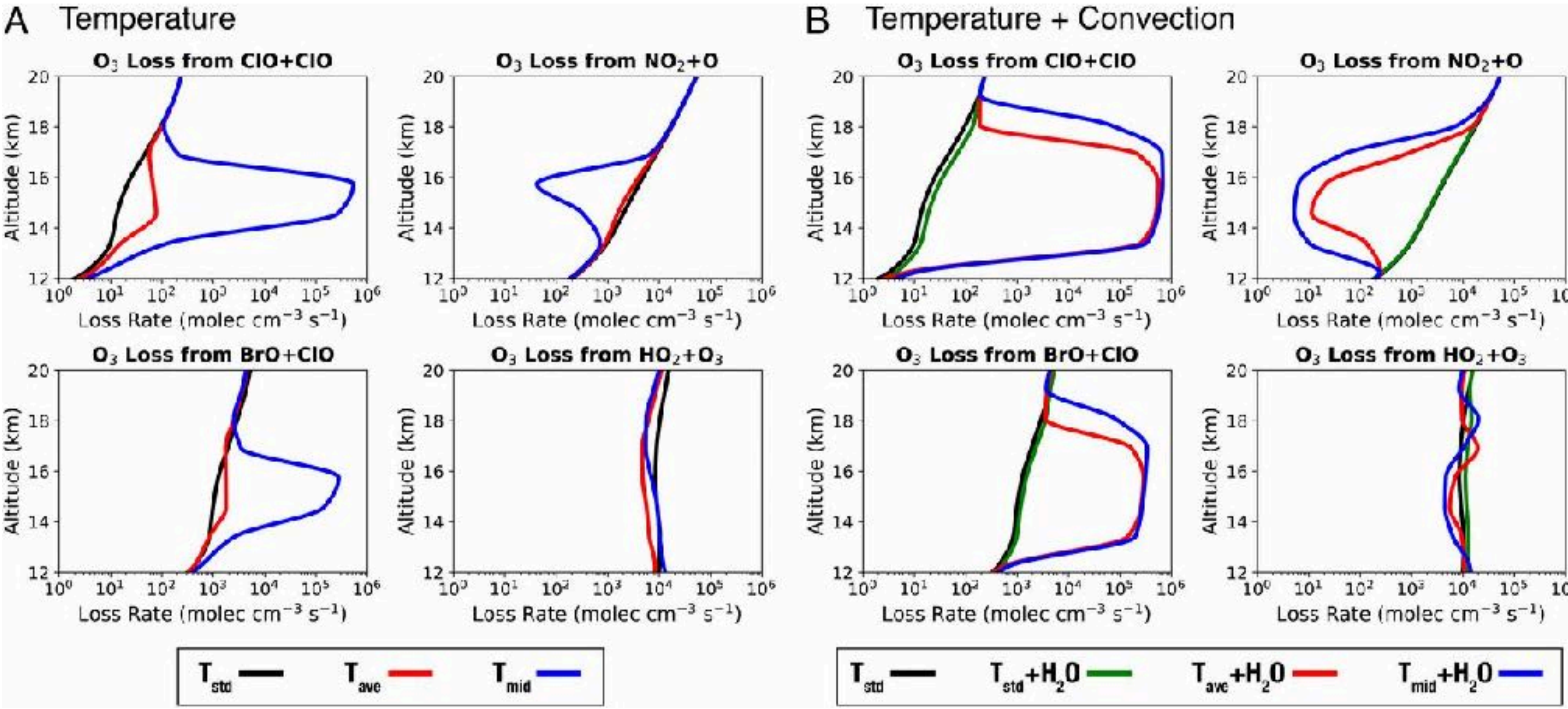


$$
\begin{array}{ll}
RLS & ClO + ClO + M \rightarrow ClOOCl + M \\
 & ClOOCl + h\nu \rightarrow Cl + ClOO \\
 & ClOO + M \rightarrow Cl + O_2 + M \\
 & 2 \times \left(Cl + O_3 \rightarrow ClO + O_2 \right) \\
\hline
\text{Net:} & O_3 + O_3 \rightarrow 3O_2
\end{array}
$$



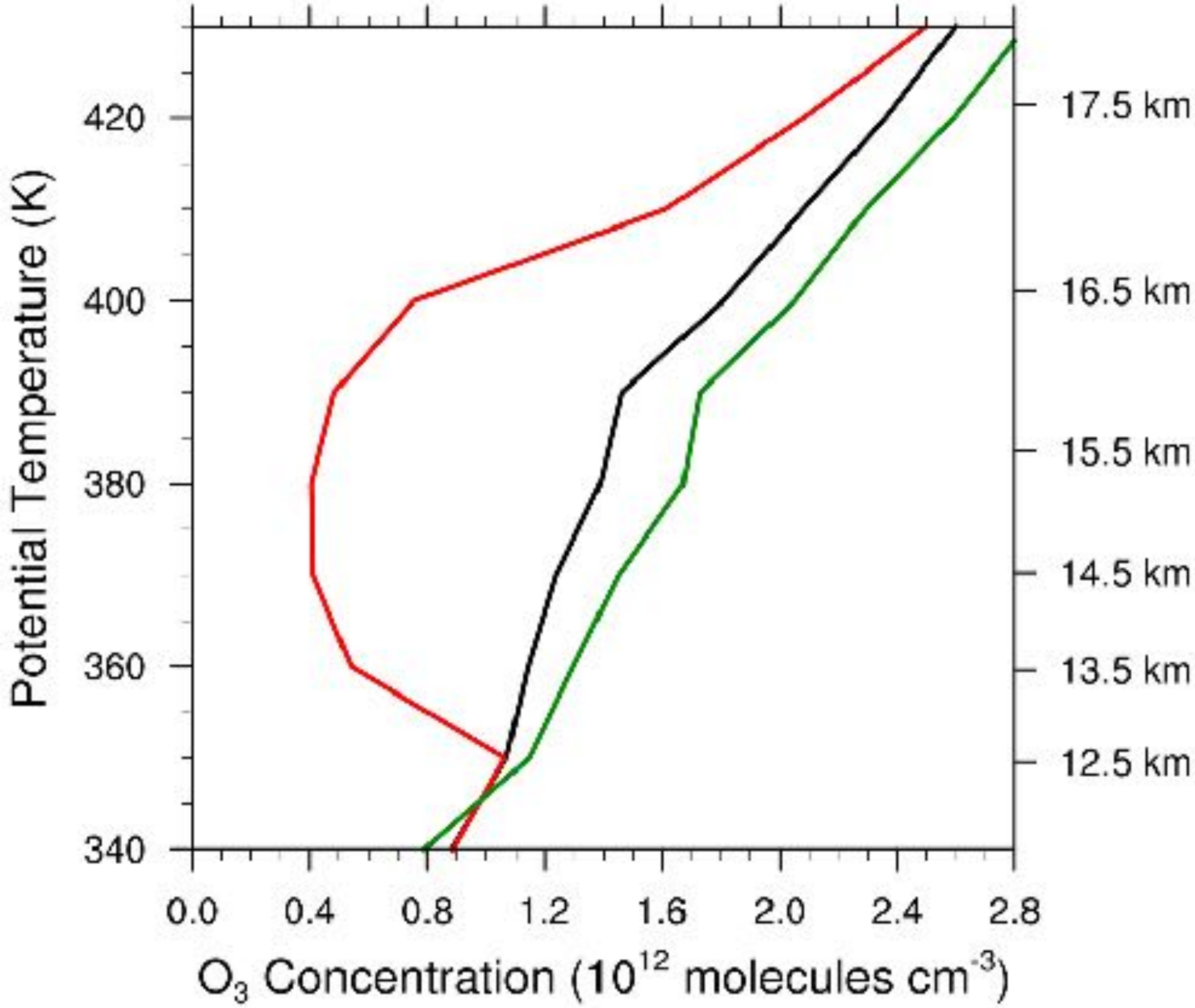
$$
\begin{array}{ll}
RLS & ClO + BrO \rightarrow Cl + Br + O_2 \\
 & Cl + O_3 \rightarrow ClO + O_2 \\
 & Br + O_3 \rightarrow BrO + O_2 \\
\hline
\text{Net:} & O_3 + O_3 \rightarrow 3O_2
\end{array}
$$



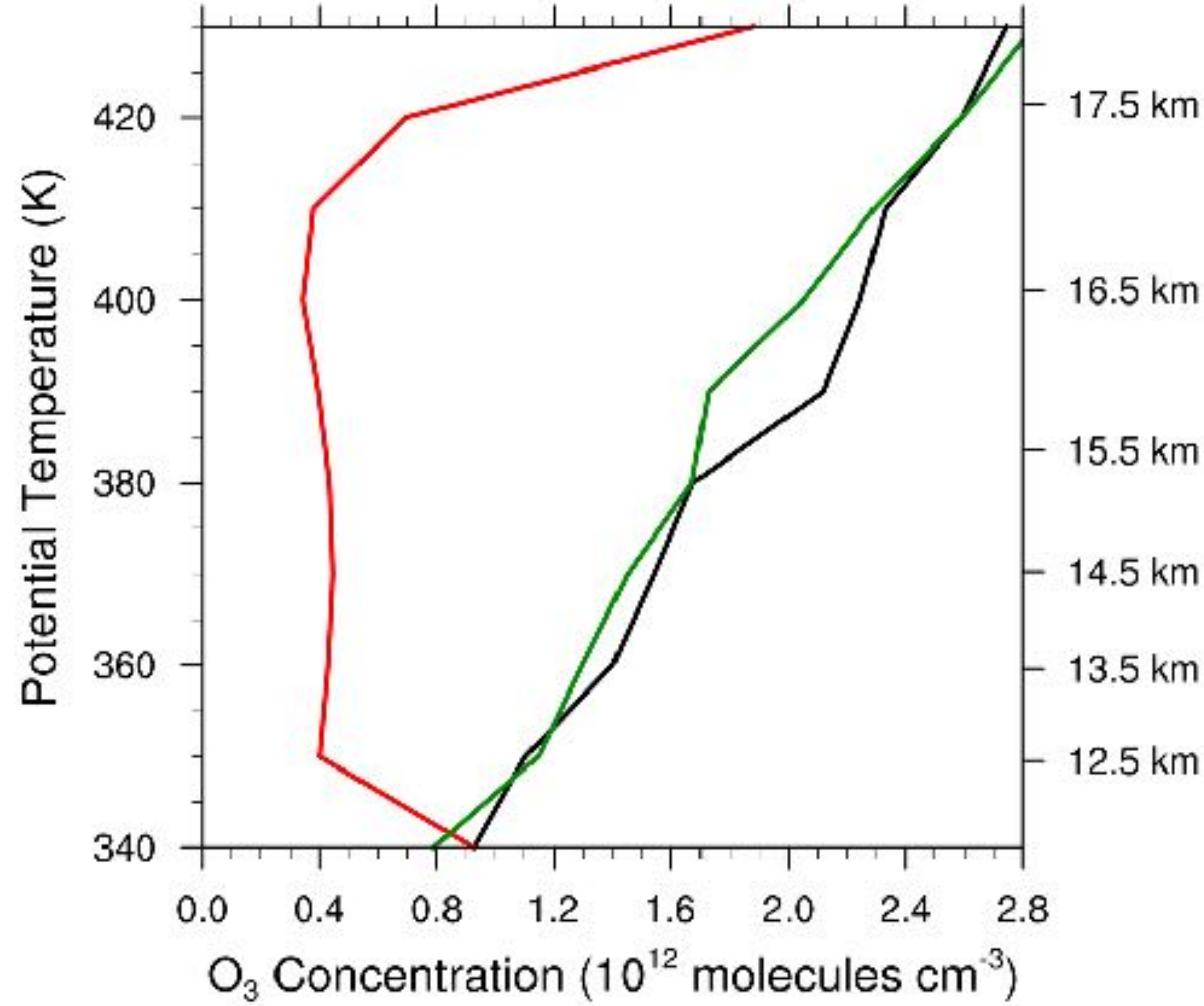


A Temperature
B Temperature + Convection
O_3 Loss from ClO+ClO
O_3 Loss from NO_2+O
O_3 Loss from BrO+ClO
O_3 Loss from HO_2+O_3
Altitude (km)
Loss Rate (molec cm^{-3} s^{-1})
T_{std}
T_{ave}
T_{mid}
T_{std}+H_2O
T_{ave}+H_2O
T_{mid}+H_2O

A

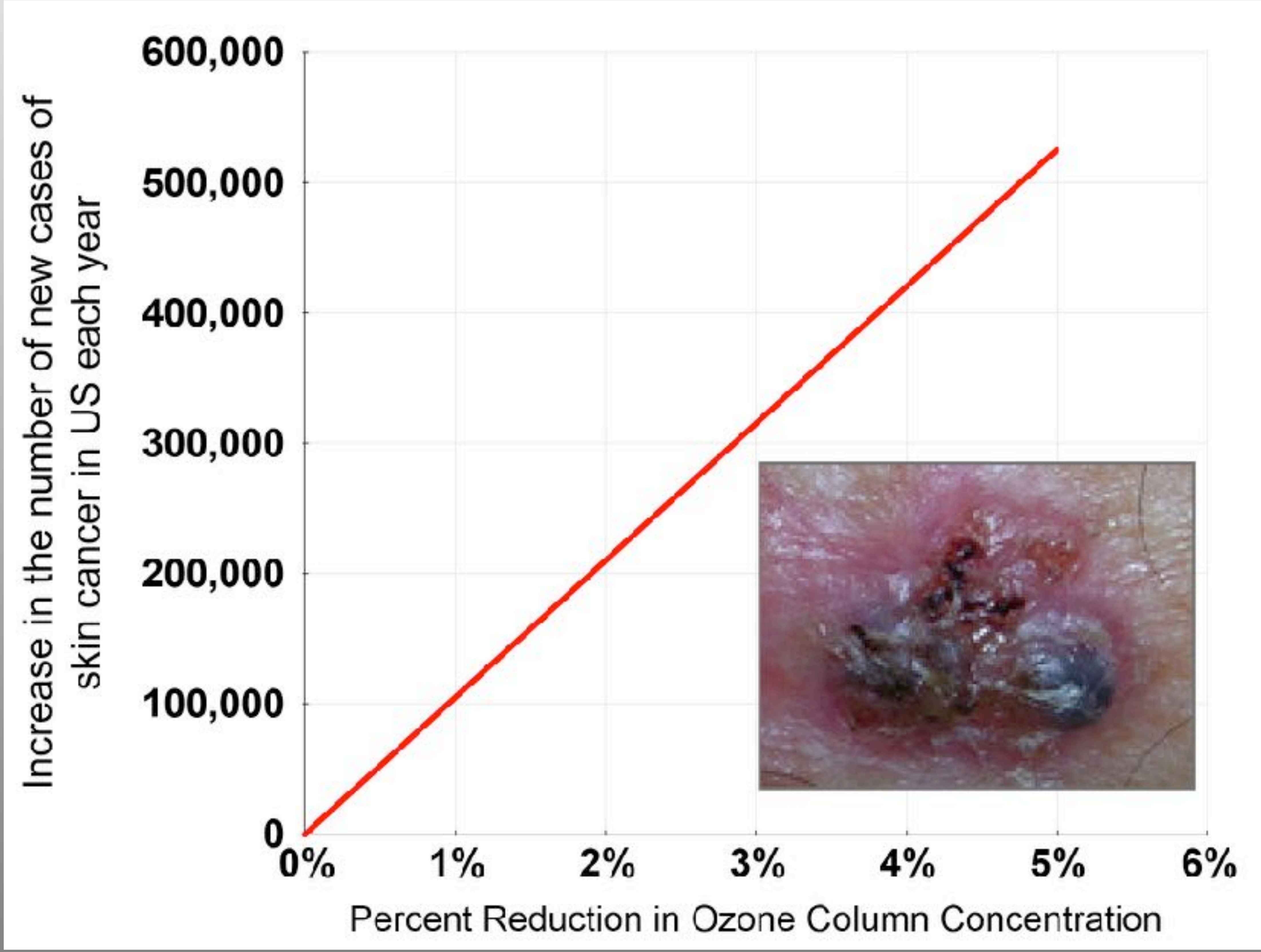


B



C

Fractional Ozone Loss Between 12 and 18 km 20 ppmv H_2O		Fractional Loss in Total Ozone Column Concentration 20 ppmv H_2O	
$[HCl]_{lower\ env}$ T_{avg} –2.48	$[HCl]_{upper\ env}$ T_{avg} –34.64	$[HCl]_{lower\ env}$ T_{avg} –0.24	$[HCl]_{upper\ env}$ T_{avg} –3.64
$[HCl]_{lower\ env}$ T_{env} –2.52	$[HCl]_{upper\ env}$ T_{env} –66.95	$[HCl]_{lower\ env}$ T_{env} –0.27	$[HCl]_{upper\ env}$ T_{env} –7.82



600,000
500,000
400,000
300,000
200,000
100,000
0
0%
1%
2%
3%
4%
5%
6%
Increase in the number of new cases of skin cancer in US each year
Percent Reduction in Ozone Column Concentration

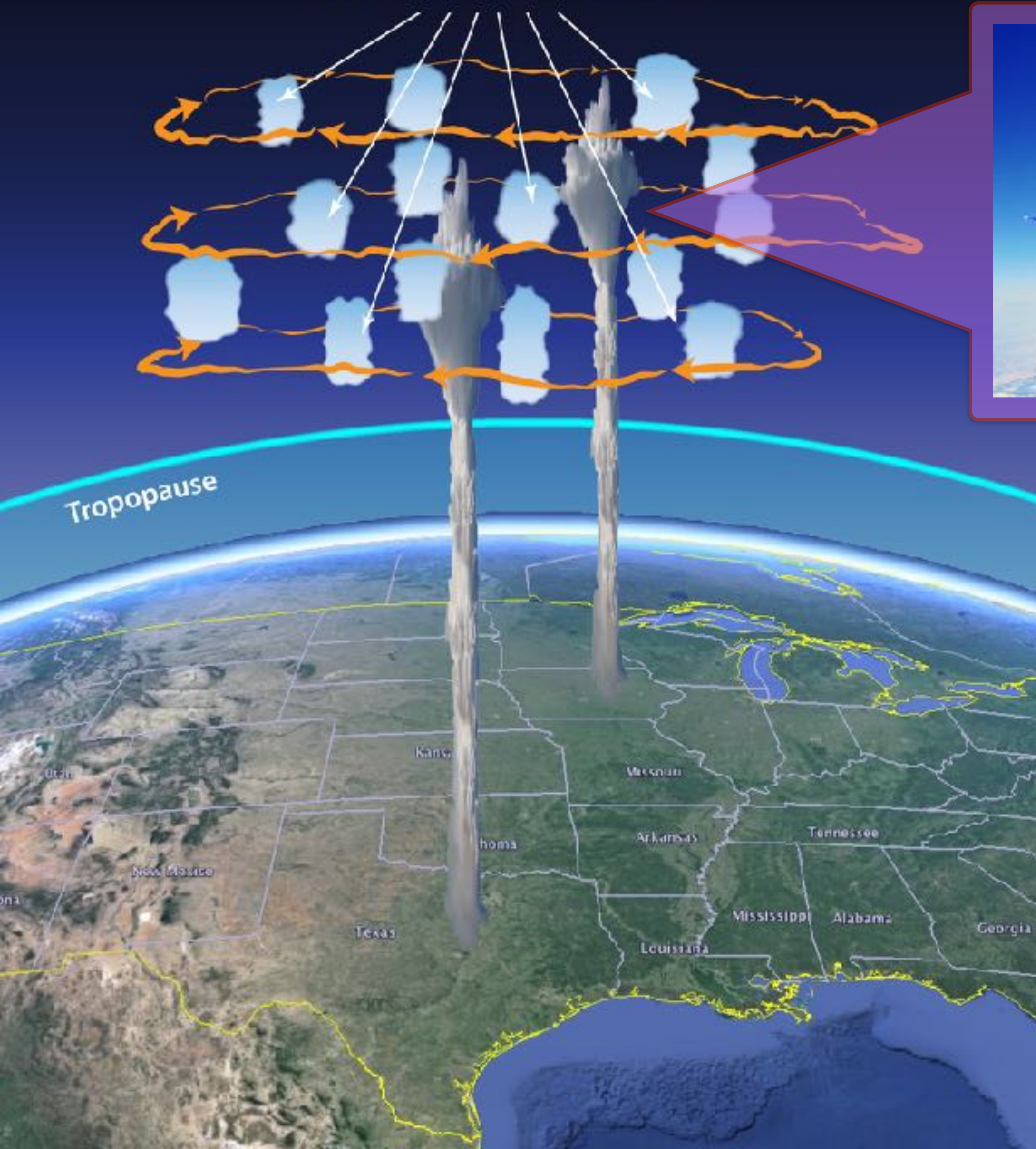
Climate, Chemistry, Technology, and Society: a University Responsibility

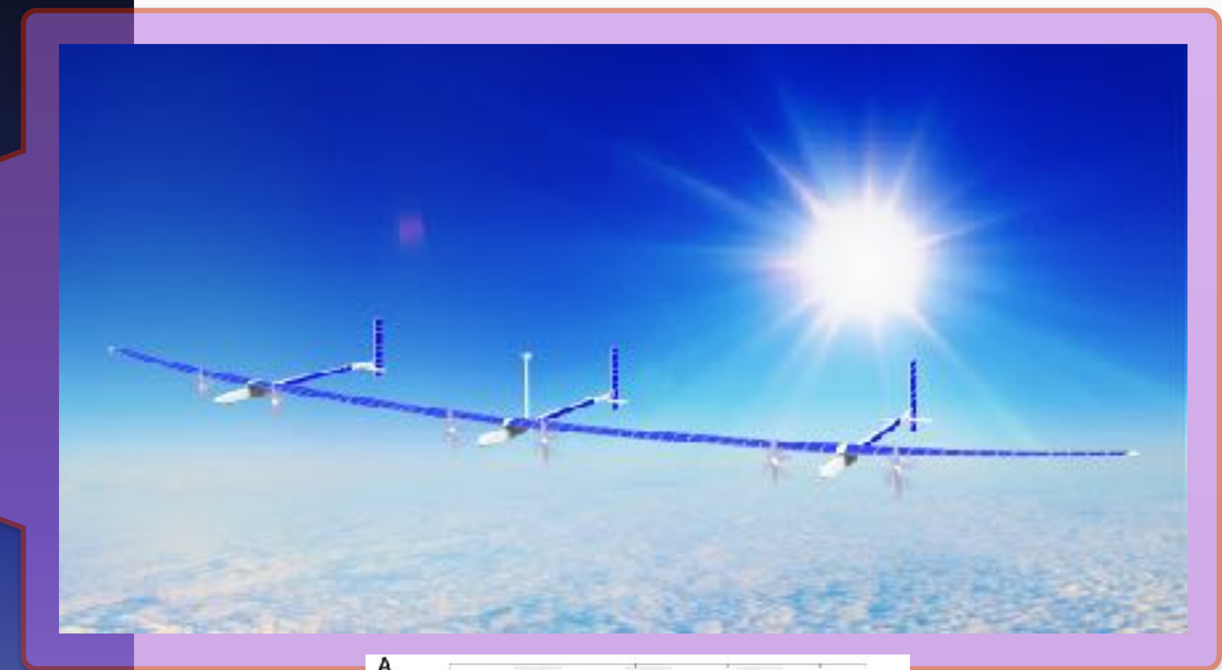
Consider the Scope, Scale and Rate of Change Taking Place

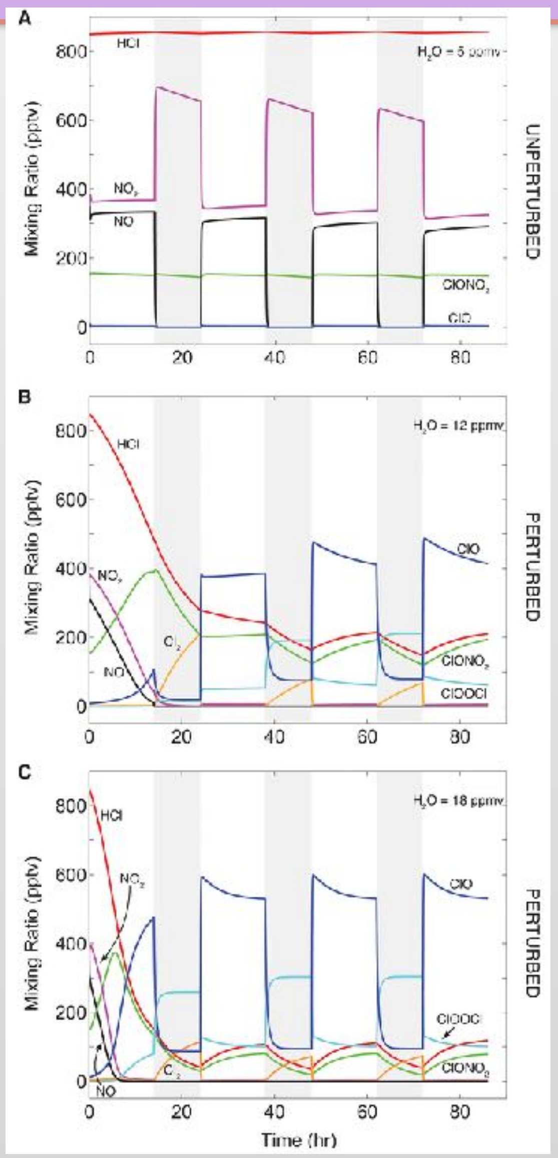
- **Major Developments in the Physical Sciences, Life Sciences, and the <u>Revolution in Technology and in *Engineering Design*</u>**

Question: How Do We Address This Problem of *Stratospheric Ozone Loss Over the US in Summer?*
Answer: Technology A New Union of (1) Materials Research for Airframe Design, (2) High Efficiency Photovoltaics, (3) Miniaturized Lasers and Electronics, New Optical Designs, (4) Advanced Robotics, Guidance and Control

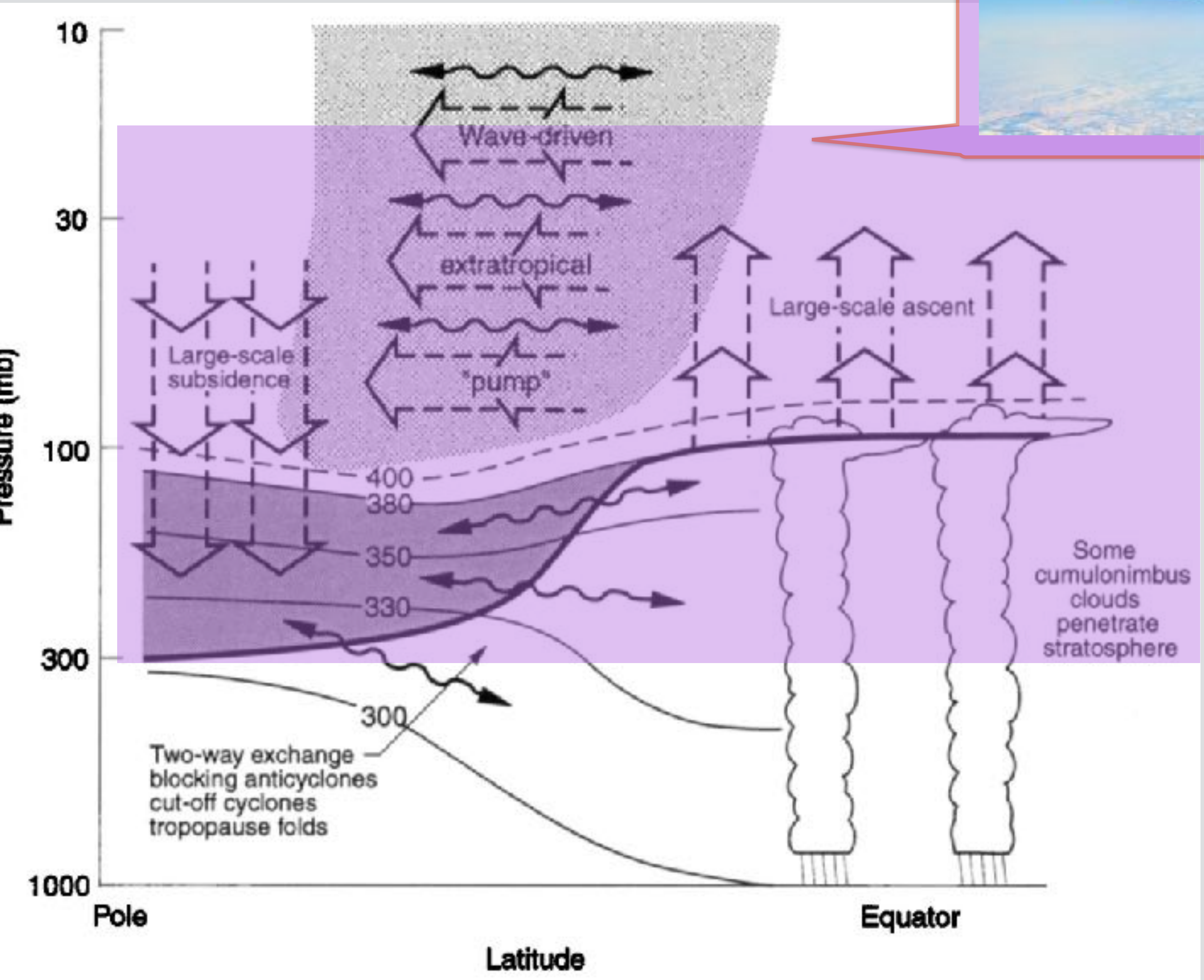
Multiple domains of depleted ozone from frequent deep stratospheric convective injection over the U.S. in summer



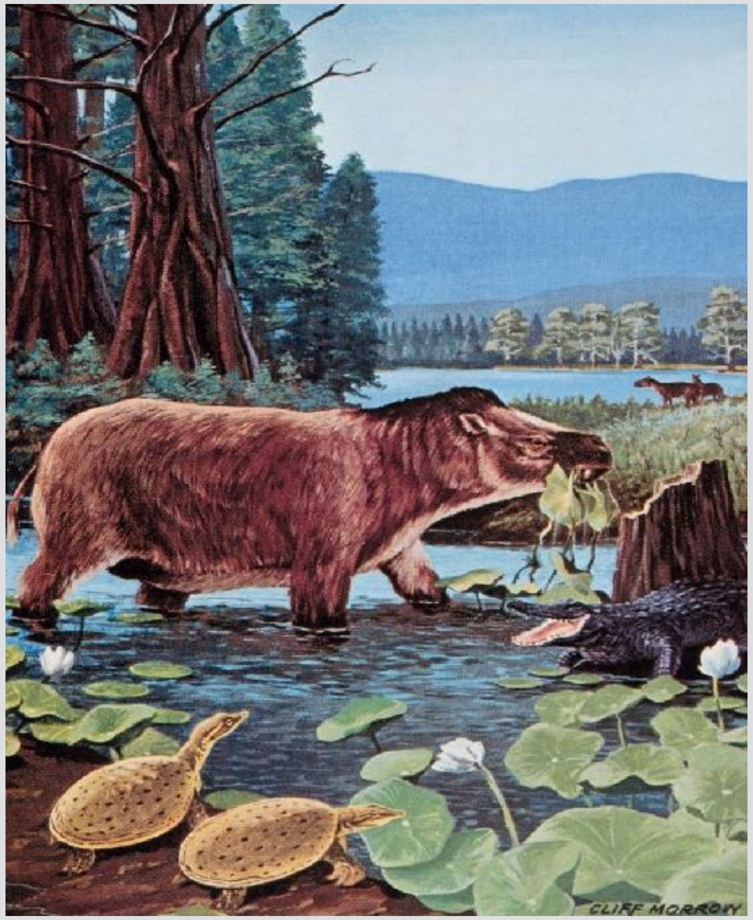




Question: How Do We Engage this New Technology to Address Other Problems?

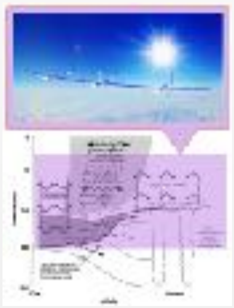


10
30
100
300
1000
Pressure (mb)
Wave-driven
extratropical
"pump"
Large-scale subsidence
Large-scale ascent
400
380
350
330
300
Some cumulonimbus clouds penetrate stratosphere
Two-way exchange
blocking anticyclones
cut-off cyclones
tropopause folds
Pole
Equator
Latitude



Major Research Topics

I. Forecasting UV Dosage Levels Over the Central US in Summer.



II. Three-dimensional mapping of the large-scale dynamics.

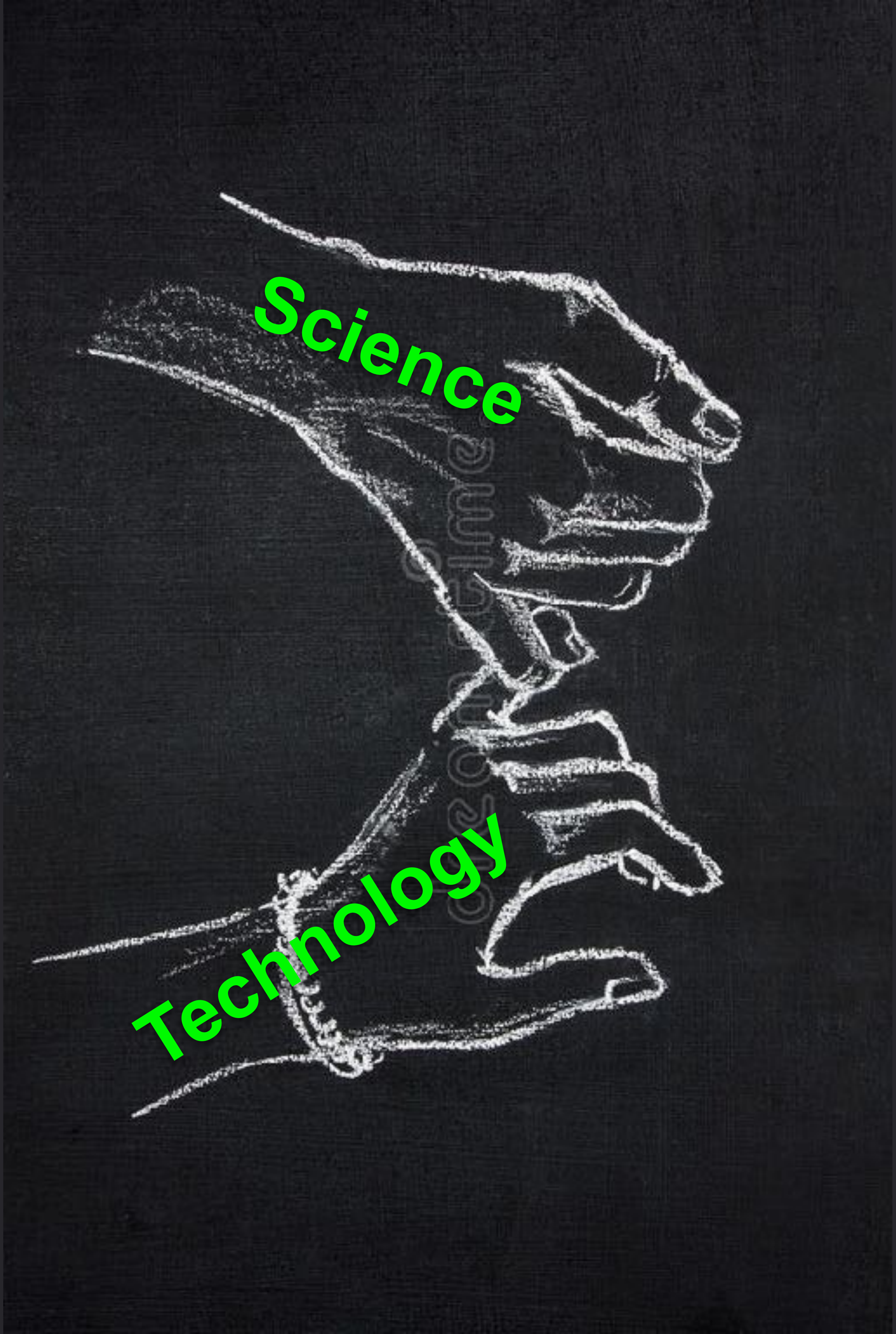
III. Forecasting Crop Productivity, Water Resources and Drought Impact:

IV. Forecasting sea level rise by mapping the glacial dynamics of Greenland.

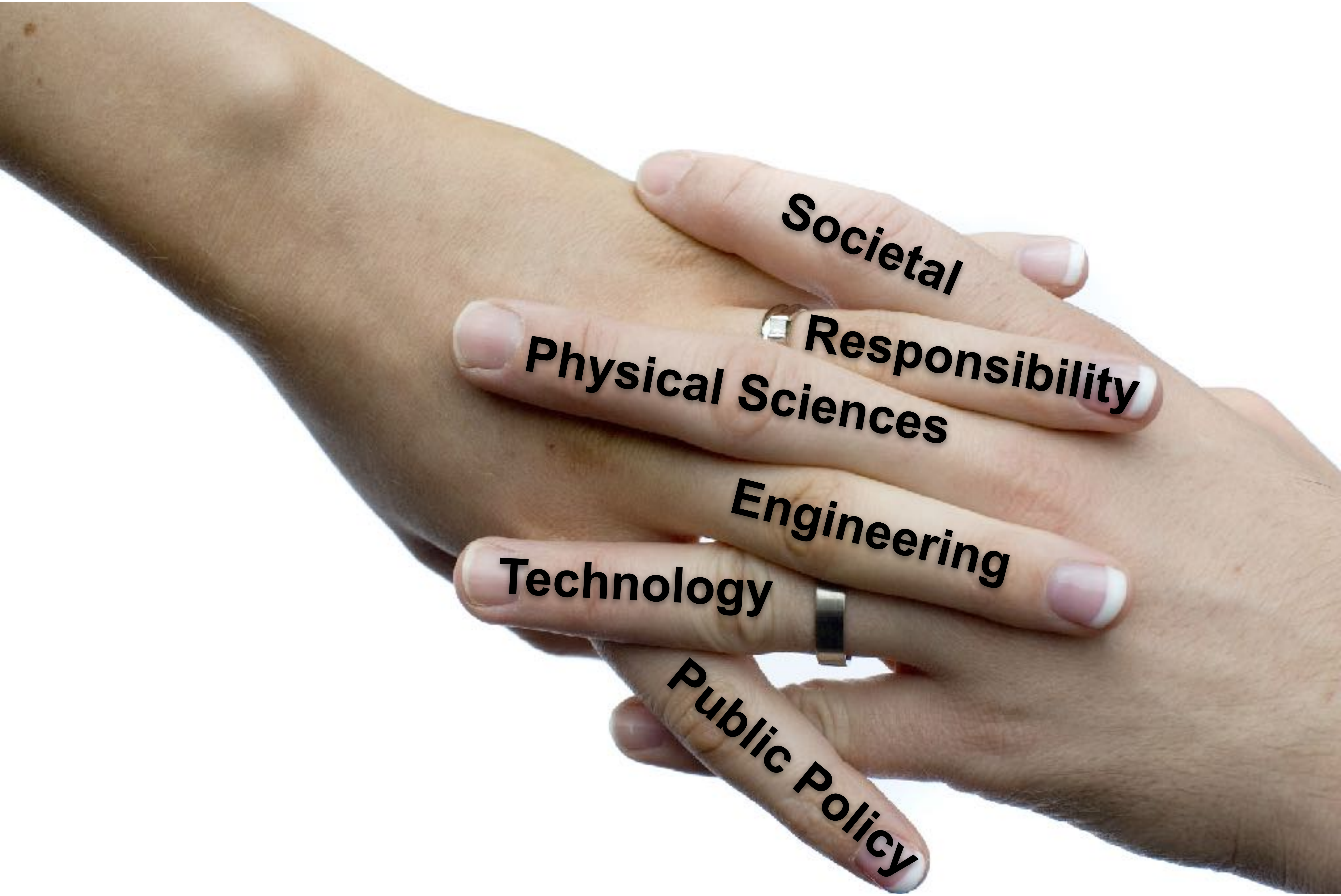
V. Forecasting Flood Intensity and Coastal Damage:

VI. Mapping the rate limiting steps from nitrate, sulfate, carbon and heavy metal emission:

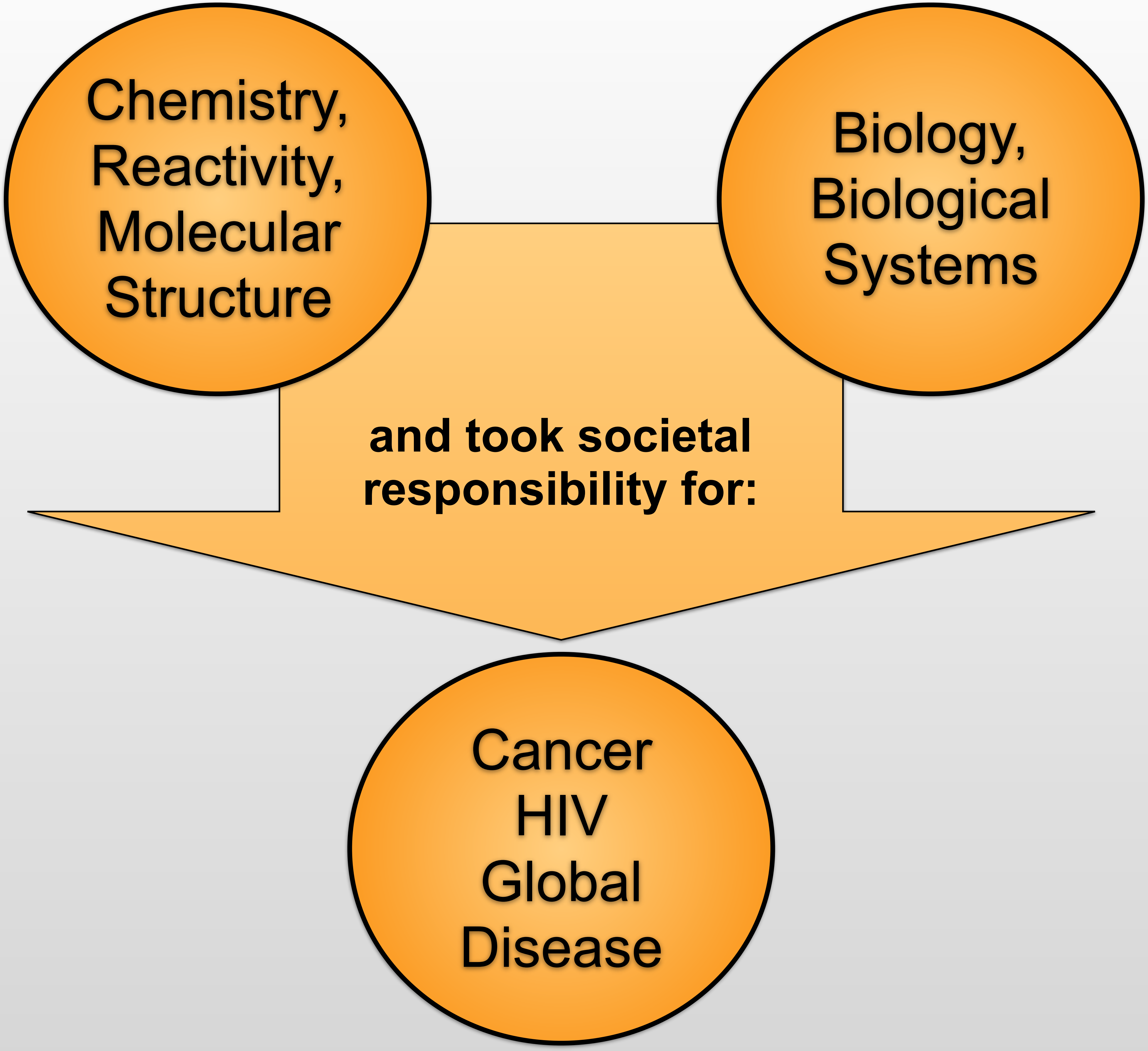
VII. Investigation of the viability of different strategies for geo-engineering


Science
Technology


Societal
Responsibility
Science
Engineering
Technology
Public Policy


Societal
Responsibility
Physical Sciences
Engineering
Technology
Public Policy

Life Sciences



All university graduates today, independent of chosen concentration, face coming to terms with a number of critical questions:

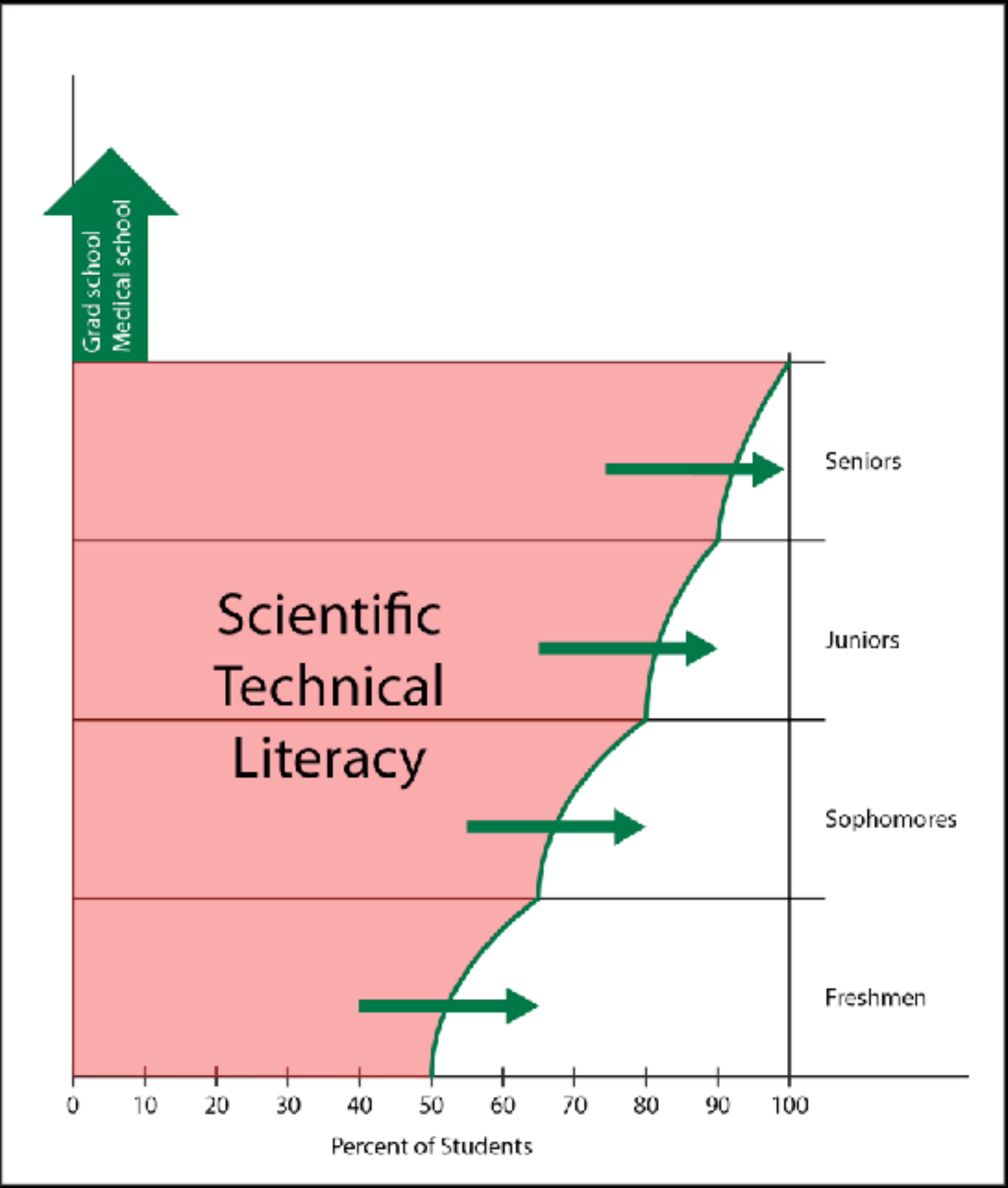
1.
What technical forces are shaping the modern world?

2.
Where are the frontiers of innovation and what implications do those advances hold for professional endeavors ...

3.
not just in technology, but also in international economics, government, ethics, journalism, public health, law and education.

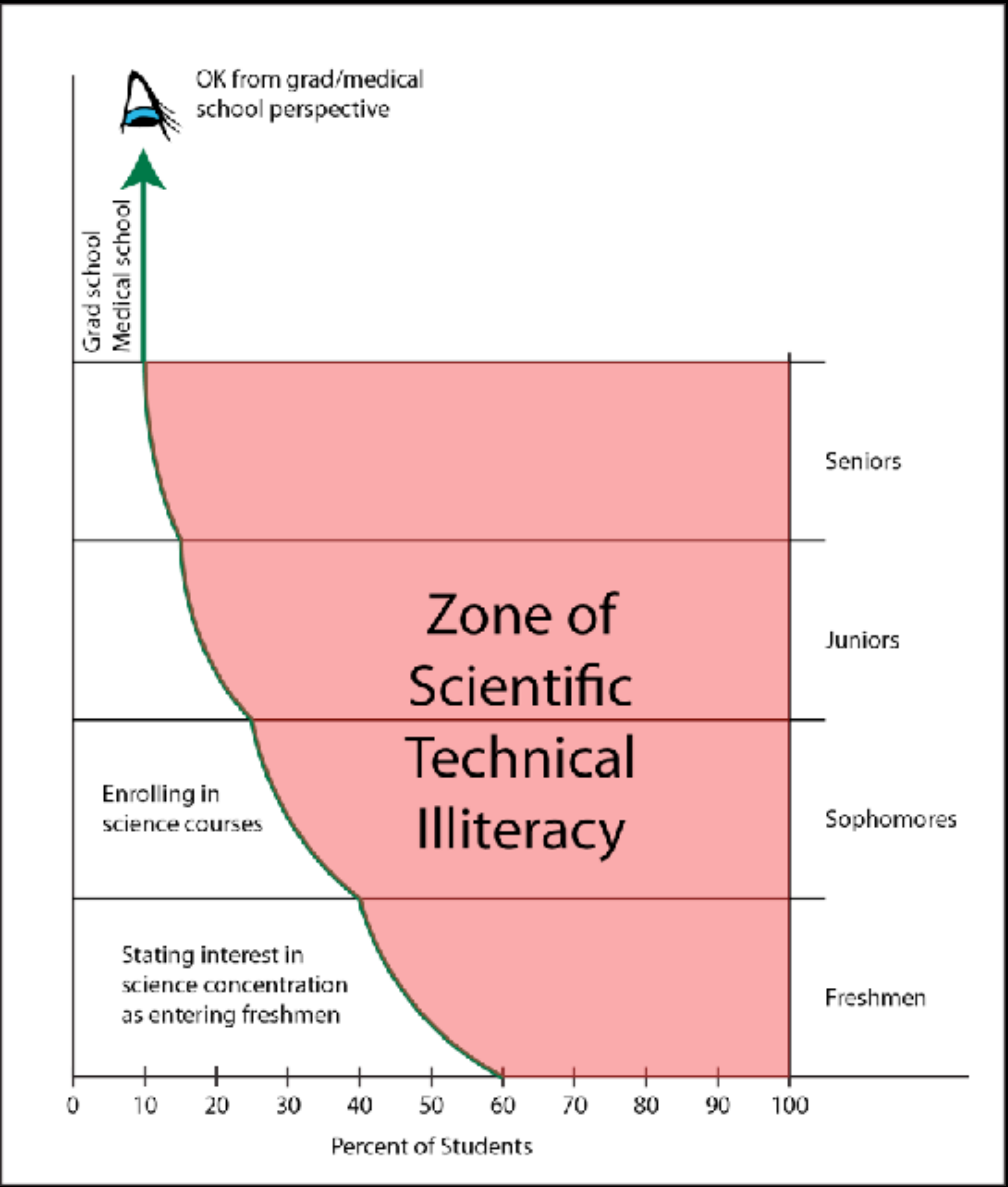
4.
Which public policy strategies are founded on sound scientific and technological understanding and which are not?

- Are universities keeping up with the pace of changes faced by graduates of the institution?
- Are universities delivering to their students what they need to know when they walk out of commencement with their new diploma?



- **The nation needs 95% of university graduates to be scientifically and technically *literate*.**
- **Without this *literacy*, it becomes virtually impossible to proactively engage in national and international decisions.**

But What is the Dynamic of Higher Education in the Physical Sciences in the US Today?



- Globally competitive economic considerations, human health and global stability should dominate public policy debates.
- But instead, public policy debates are dominated in large part by a lack of depth, essential information and perspective that should be an integral part of a modern university education.

This very large attrition from the physical sciences stems from a number of causes:

- We only want students with the “right stuff” for graduate school,
- We gave you the atom bomb, NMR, radar, etc. and we are owed research support in perpetuity, and
- We have the right to flunk your kids out of freshman physics and chemistry with impunity.

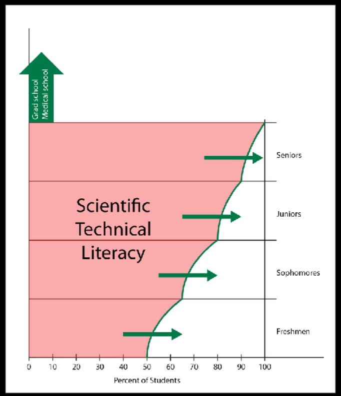
Critically Needed:

New Strategic Approach for Introductory Courses in the Physical Sciences

Research has shown:

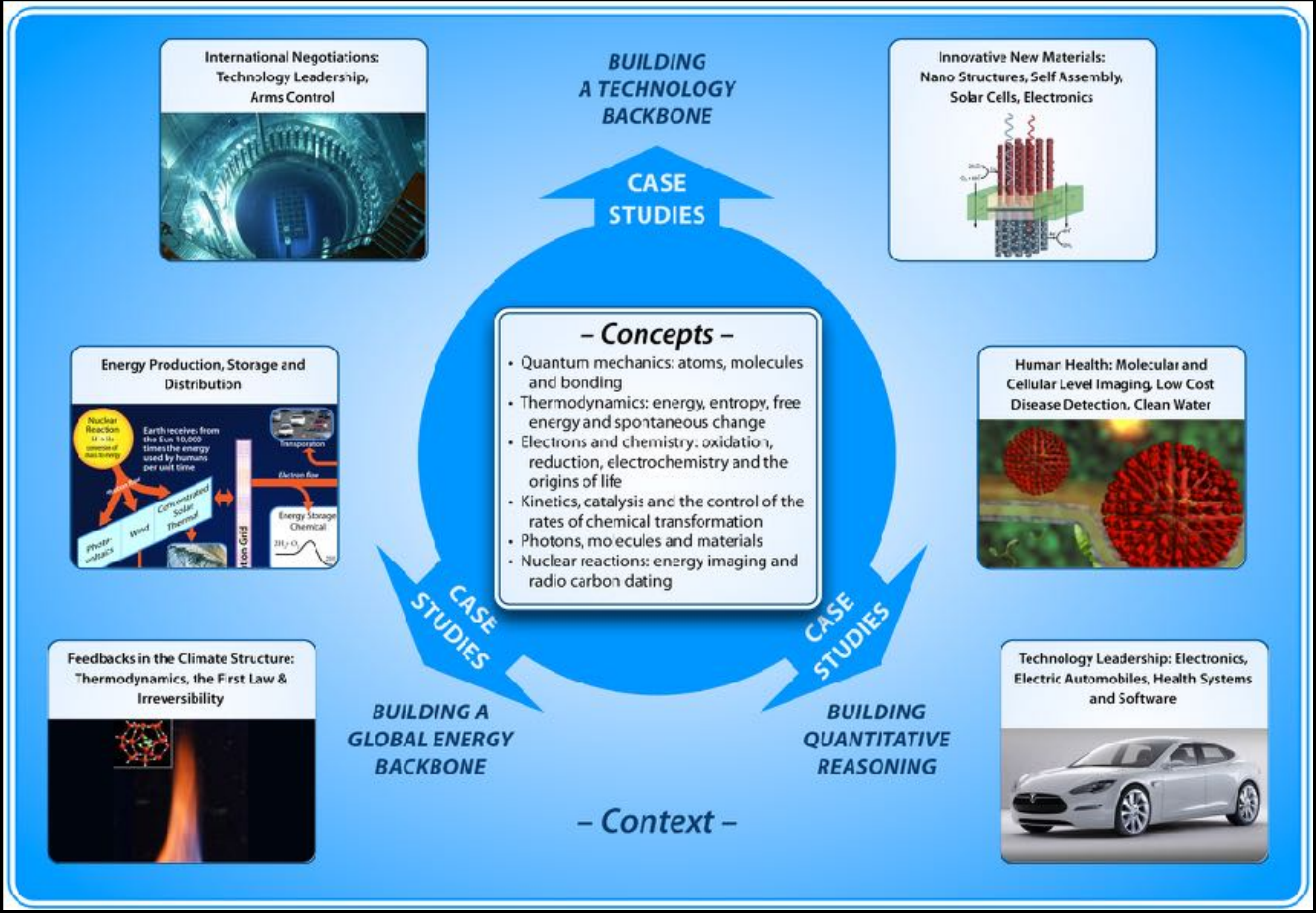
1. Significant contributor is that introductory chemistry & physics are taught as isolated subjects.

2. without a compelling context, this creates an *exclusive* rather than *inclusive* message



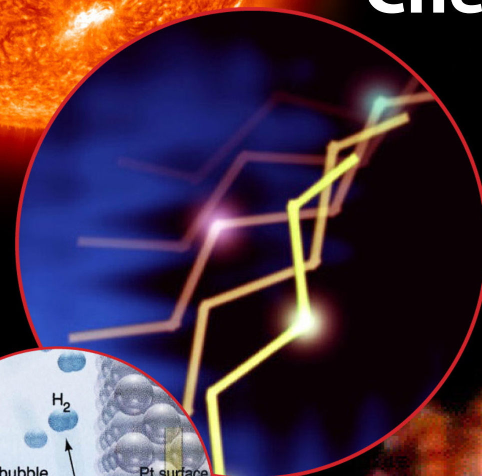
Redesigned Introductory Chemistry to be *Inclusive*:

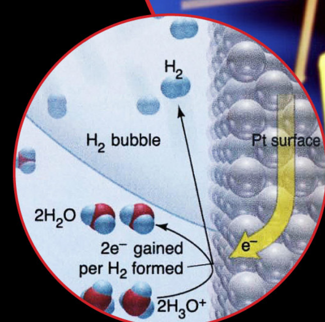
- Contextual Strategy:



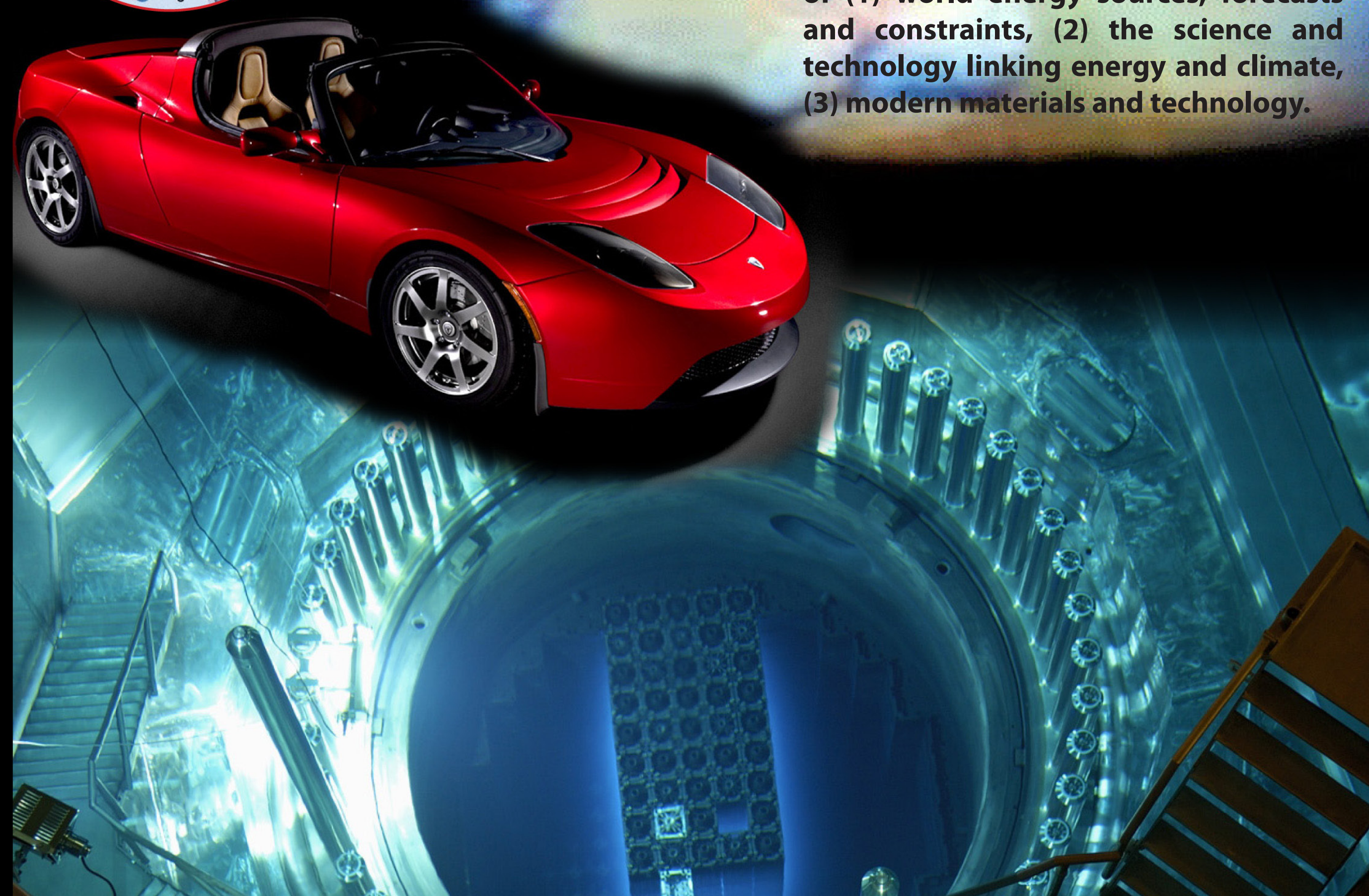
Physical Sciences 11:

Frontiers and Foundations of Modern Chemistry: A Molecular and Global Perspective

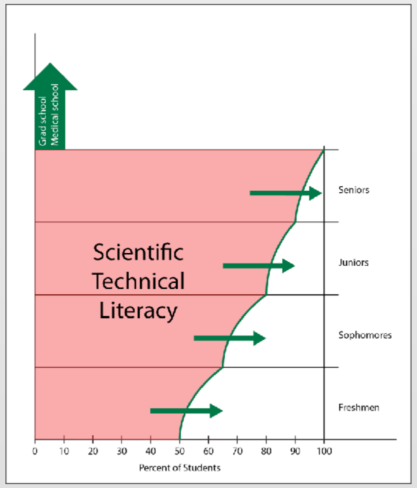


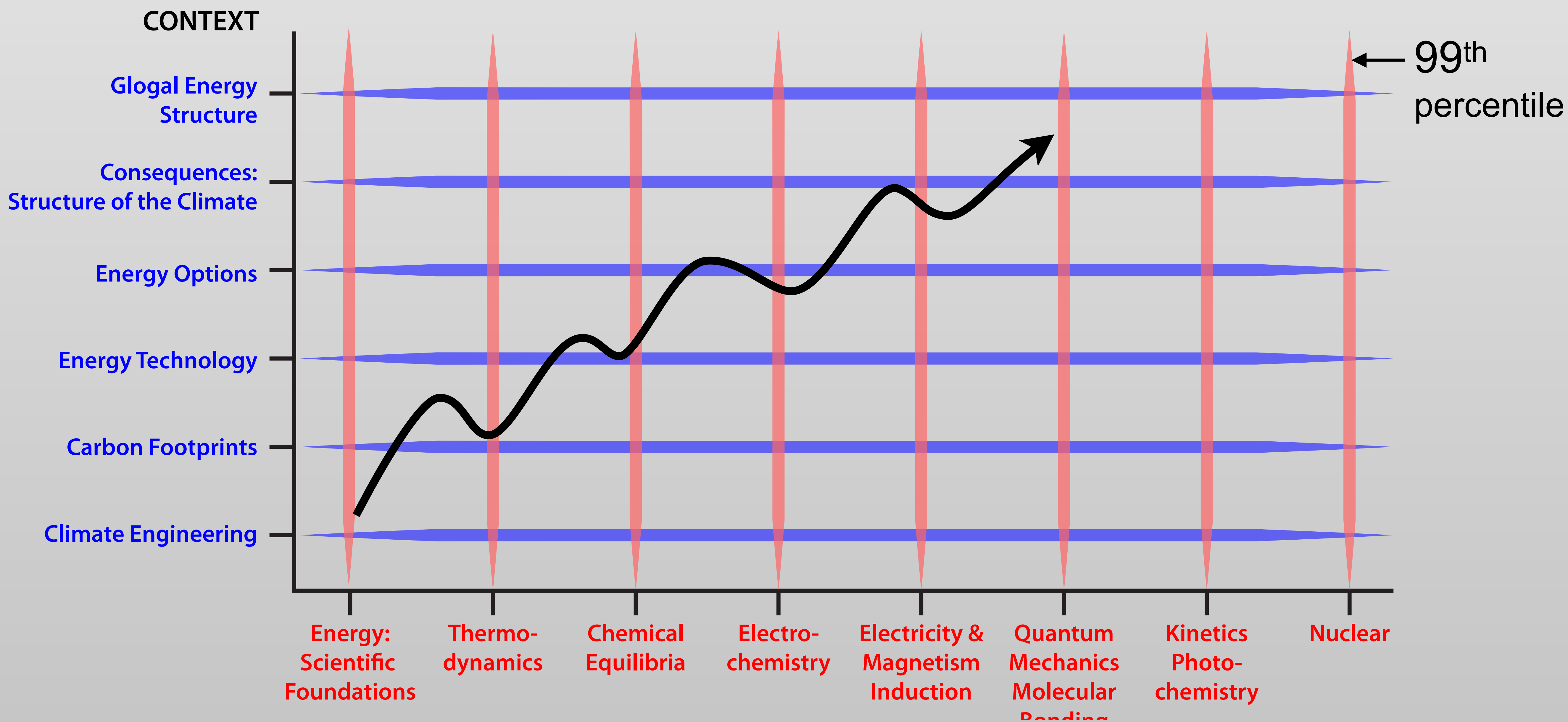


Revolutionary developments in the union of chemistry and physics hold the key to solving unprecedented problems at the intersection of science, technology, and an array of rapidly emerging global scale challenges. In particular concepts central to energy and its transformations, thermodynamics, energy, entropy and free energy, quantum mechanics, atomic structure, molecular bonding, kinetics, catalysis, equilibria and acid-base reactions, and nuclear chemistry are presented with emphasis on the context of (1) world energy sources, forecasts and constraints, (2) the science and technology linking energy and climate, (3) modern materials and technology.



Course is designed to be Inclusive: It is not designed to be easy

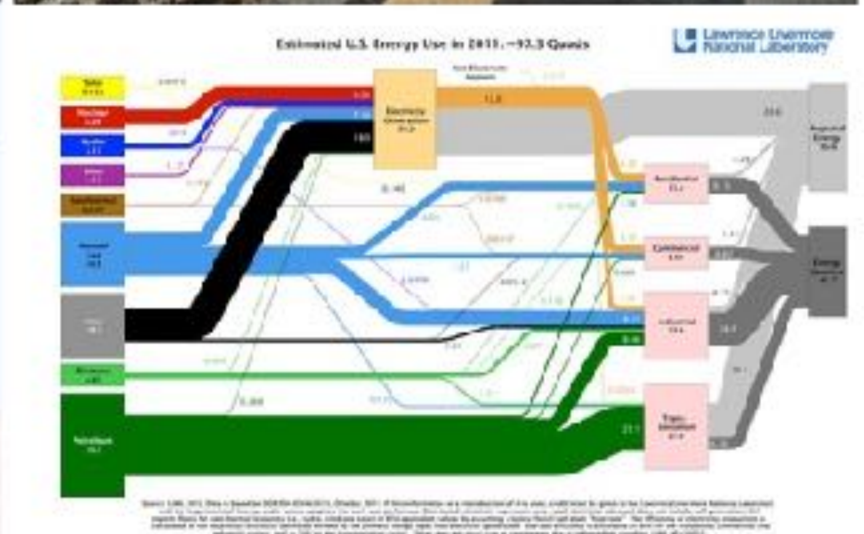


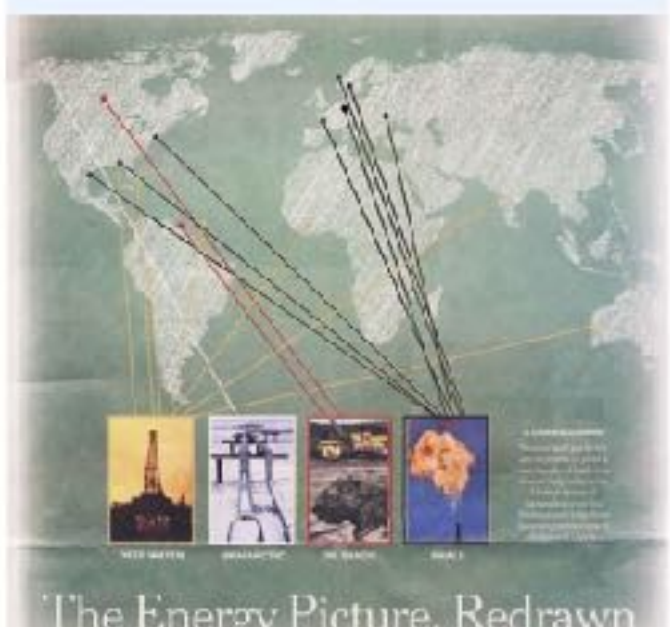


Physical Sciences 11

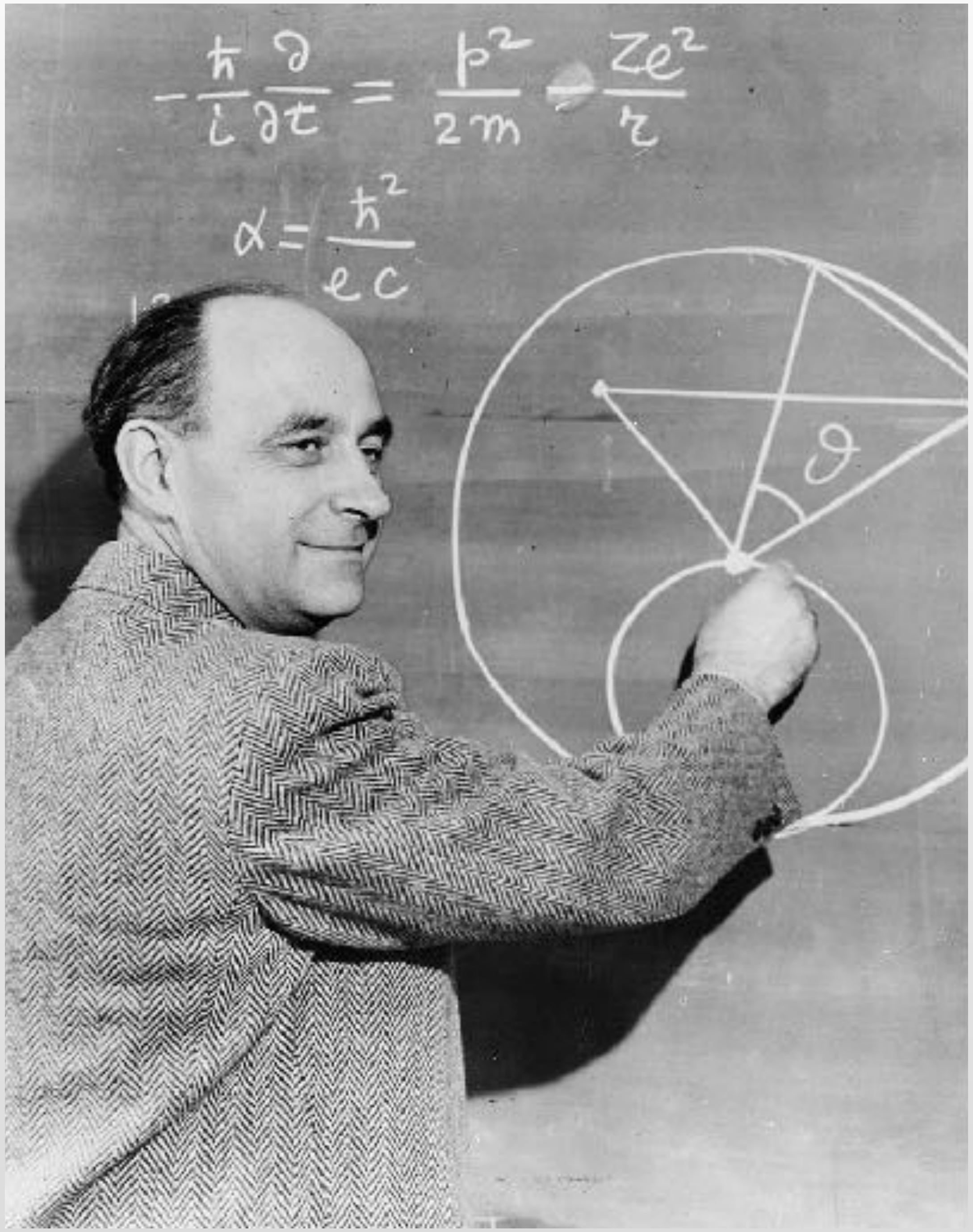
Global Calculations

The 50 Questions





Problem-Solving - Estimation and Orders of Magnitude



Developing a good sense of how to use your physical intuition for solving problems involves learning the technique of deciding which approach to solving a problem tends to work more "easily" than other possible approaches.

Some Questions That All University Graduates Should Know the Answer to:

1. What is the ratio of power received from the Sun to the power consumed by the human endeavor?
2. How do you calculate global energy demand? The increase in global energy demand?
3. To meet that demand do we need to build a 600MW power plant every month for the next 40 years? Every week? Everyday? Two every day?
4. When we trace the flow of energy from its production to its end use, why is 65% lost to waste? What controls that?

Some (More) Questions That All University Graduates Should Know the Answer to:

5. What fraction of petroleum imports is from the Western Hemisphere, what fraction from the Middle East?
6. How do you calculate energy to propel a gasoline automobile 100km? An electric car 100km? How much does the nation spend on gasoline each year? If the fleet was electric how much would the nation spend? By what fraction would that increase electricity demand?

END